NEW

EVERYTHING YOU NEED TO KNOW ABOUT

THE SOLAR SYSTEM

DISCOVER THE SECRETS OF OUR NEIGHBOURING PLANETS, MOONS AND MORE

INNER PLANETS

Explore Mercury, Venus, Mars and Earth

MAKING OUR MOON

Learn how an ancient planetary impact shaped our nearest satellite

+PLUS 25 FASCINATING FACTS ABOUT THE SOLAR SYSTEM, DWARF PLANETS AND MORE!

Digital Edition

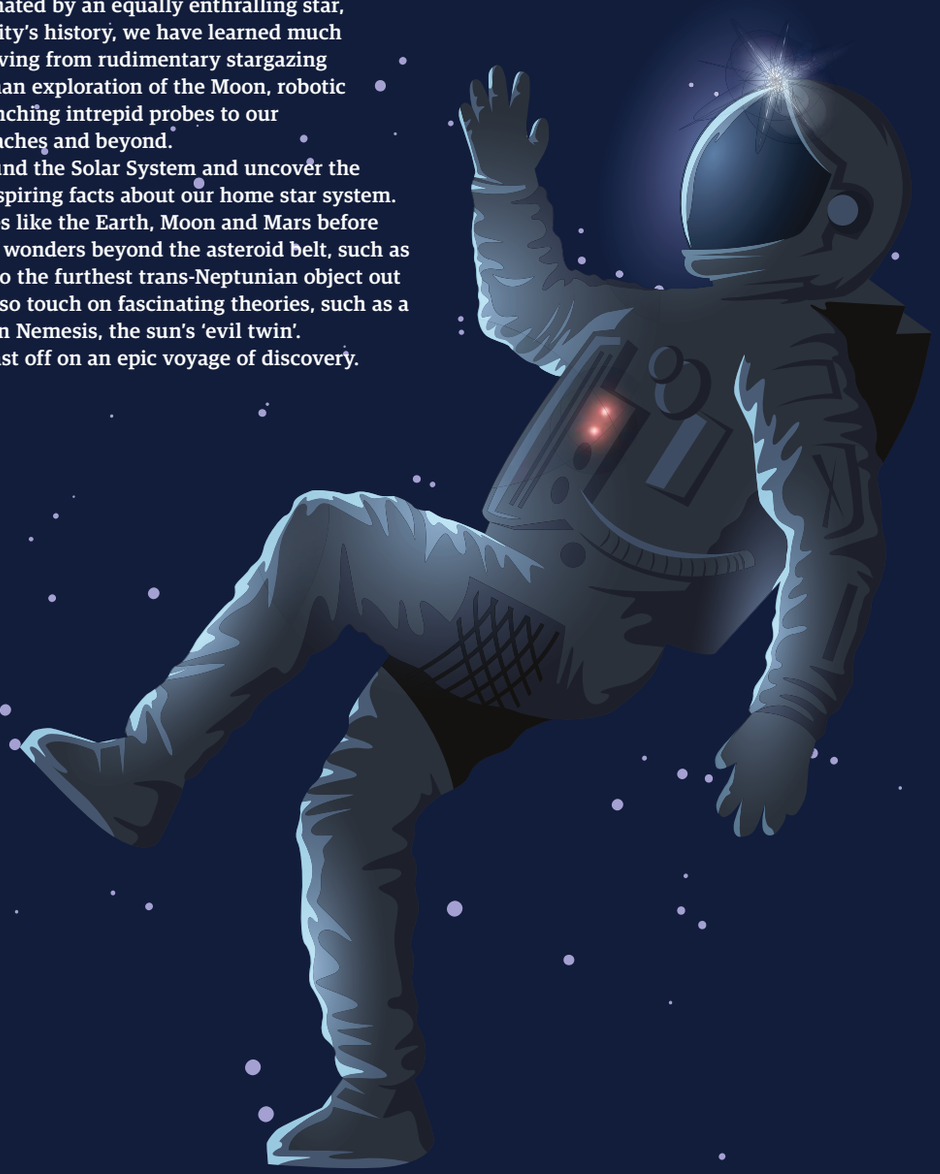
FUTURE
FIRST EDITION

WELCOME

The Earth's nearest neighbours are a fascinating array of planets, moons and asteroids, illuminated by an equally enthralling star, the Sun. Throughout humanity's history, we have learned much about the Solar System, evolving from rudimentary stargazing with early telescopes to human exploration of the Moon, robotic expeditions to Mars and launching intrepid probes to our neighbourhood's furthest reaches and beyond.

Join us as we journey around the Solar System and uncover the most fascinating and awe-inspiring facts about our home star system. We'll stop off at familiar faces like the Earth, Moon and Mars before journeying to distant, far-off wonders beyond the asteroid belt, such as Neptune, Pluto and beyond to the furthest trans-Neptunian object out there, 'FarFarOut'. We will also touch on fascinating theories, such as a distant ninth planet and even Nemesis, the sun's 'evil twin'.

Strap in and prepare to blast off on an epic voyage of discovery.




FUTURE

THE SOLAR SYSTEM

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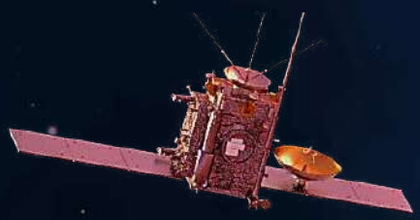


EVERYTHING YOU NEED TO KNOW ABOUT...

THE SOLAR SYSTEM

JOIN US ON A TOUR THROUGH OUR CURRENT UNDERSTANDING OF THE PLANETARY SYSTEM WE CALL HOME

INTRODUCING THE SOLAR SYSTEM

Our Solar System consists of the area influenced by the Sun and, apart from occasional stray visitors from interstellar space, everything it contains. Aside from the Sun, its main components are the eight major planets, their moons and rings, a handful of worlds classified as dwarf planets and vast numbers of smaller bodies made of varying amounts of rock and ice, which are broadly termed asteroids and comets. Most of these objects orbit in a plane roughly in line with the Sun's equator and in the same direction as the Sun's rotation – anticlockwise when viewed from 'above' the plane.

The four innermost planets are mostly composed of dense rock and metal. Earth is the largest of these 'terrestrial' planets, with Venus almost the same size, Mars significantly smaller and Mercury the smallest of all. A large gap separates the orbit of Mars from that of Jupiter, the innermost gas giant and the largest planet in the entire Solar System, with a diameter of 11.2 Earths. Saturn is somewhat smaller, and outer Uranus and Neptune are near twins, both about four times the diameter of Earth.

The entire Solar System sits within the Milky Way – a vast spiral galaxy within which our Sun is just one of several hundred billion stars. At about 26,000 light years from the centre, it takes some 230 million years to complete one trip around the galaxy.

AN EVOLVING SYSTEM

Our neighbourhood hasn't always been quiet

Although today's Solar System seems stable, it represents just a snapshot in a long history of change and evolution. Asteroids and comets in planet-crossing orbits are doomed to suffer disruption of some kind on astronomical timescales, and so their supplies must continuously be replenished. In the first billion years of Solar System history, however, changes were far more dramatic. It's increasingly clear that the giant planets formed closer to the Sun – and to each other – than they are now, and a subsequent gravitational tug of war saw their orbits evolve and change. Jupiter may have first migrated even closer to the Sun, scattering vast numbers of icy objects from the outer edge of today's asteroid belt and beyond into extreme elliptical orbits to form the Oort Cloud, before reversing its track. Neptune may have started its life closer to the Sun than Uranus before their own complex gravitational dance swapped them over, pulling Uranus' axis of rotation over to its extreme 98-degree angle. Some computer models even suggest that in order to reach the current configuration of giant planets, there must once have been a fifth Neptune-sized world that was long ago ejected from the Solar System entirely, or perhaps flung into exile amid the comets of the Oort Cloud.

ORIGINS

Evidence from rock grains in ancient asteroids suggests the Solar System began to form about 4.57 billion years ago. Like other stars, the Sun was born from a collapsing cloud, or nebula, rich in gas and dust. As the centre of the cloud grew hotter and denser it began to spin more rapidly, while material around it flattened out into a rotating disc. Dust grains collided and stuck together in the disc, perhaps growing step by step through chance collisions until they had sufficient gravity to draw in more material from around them, or perhaps forming huge clouds of orbiting 'pebbles' that underwent sudden collapse into larger protoplanets when they became unstable.

Meanwhile, as the Sun became hot enough to shine properly, rising temperatures caused easily melted chemicals to evaporate as far out as an 'ice line' in the present-day asteroid belt. Simultaneously, fiery radiation from the newborn Sun and a solar wind of ionised particles blowing out from its surface began to drive gas outwards. While the worlds of the inner Solar System had to form mostly from dry, rocky materials, those farther out incorporated substantial amounts of ice, and in the case of the largest planets, were also able to keep hold of huge gaseous atmospheres thanks to their powerful gravity.

THE SUN

Our local star controls conditions across the wider Solar System. With a visible diameter of 1.39 million kilometres (860,000 miles), it accounts for some 99.8 per cent of the Solar System's entire mass and has a composition dominated by hydrogen – the lightest and simplest gas in the universe.

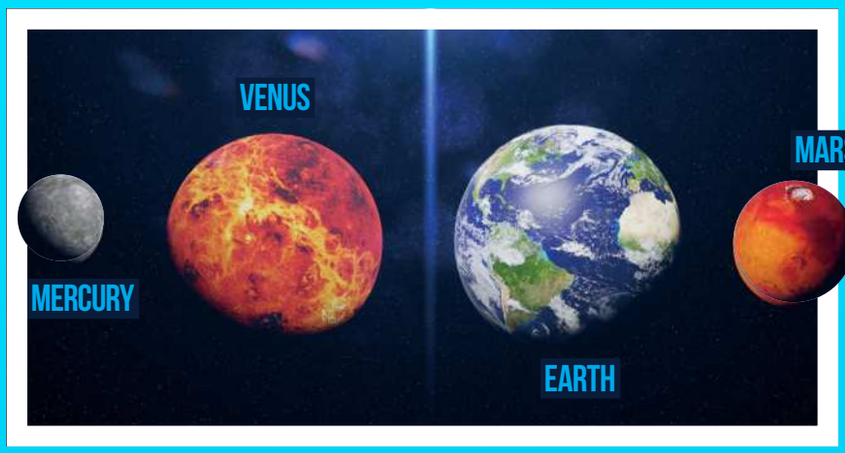
The Sun shines by nuclear fusion, a process that forces hydrogen nuclei together in the core to form nuclei of helium, the next lightest element. Energy is released in the process as photons of high-energy radiation gradually force their way outwards through the overlying layers, losing energy as they do, and keeping the Sun's interior hot. The Sun's incandescent visible surface, or photosphere, marks the region where its gas becomes cool and sparse enough to be transparent, and visible, infrared and ultraviolet light can escape. This surface has an average temperature of around 5,500 degrees Celsius (9,932 degrees Fahrenheit), although dark sunspots, created where the Sun's tangled magnetic field bursts from its surface, can be a couple of thousand degrees cooler.

Above the photosphere, the Sun's upper layers are home to violent activity that varies, along with sunspot numbers, in an 11-year cycle. The cycle significantly affects the shape of the Sun's corona, or outer atmosphere, which typically extends to several times its visible diameter before merging with the solar wind of particles blowing out across the Solar System.

BELOW (TOP): Everything in the Solar System formed from a protoplanetary disc around the Sun

BOTTOM: The Sun sends out ionised particles that carry through to the outer reaches of the Solar System

"AS THE SUN BECAME HOT ENOUGH TO SHINE PROPERLY, RISING TEMPERATURES CAUSED EASILY MELTED CHEMICALS TO EVAPORATE"



© Alamy

LEFT: Our home planet is the largest of the four rocky bodies closest to the Sun

ROCKY PLANETS

A variety of factors have shaped the evolution of the terrestrial planets – most importantly their size, composition and distance from the Sun. As a rule, the larger a planet is, the hotter its interior will remain, giving rise to a more complex structure and potentially a molten metallic core. Size and mass determine a planet's gravity, which along with its temperature and the presence of a protective magnetic field influence how well it can hold on to an atmosphere. These factors influence the chemicals that can exist on its surface.

It's likely that all four rocky planets were bombarded by icy objects from farther out in the Solar System during or shortly after their formation, returning water to their surfaces. Venus, Earth and Mars all once had oceans of liquid water, but Venus' was lost to a runaway greenhouse effect early in its history, leaving behind an arid, hellish landscape. The weak gravity and lack of a protective magnetic field around Mars, meanwhile, allowed much of its atmosphere and water to escape into space, cooling the surface until most of the remaining water became locked in permafrost and the polar ice caps. Venus and Mars show signs of geological activity in the relatively recent past, but this mostly takes the form of volcanism, while activity on Earth is far more complex and continuous.

GIANTS OF GAS AND ICE

The giant planets of the outer Solar System are broadly divided into two pairs: the inner gas giants Jupiter and Saturn, dominated by huge envelopes of hydrogen, and the outer ice giants Uranus and Neptune, made of more complex chemicals such as water, methane and ammonia. All four have deep outer atmospheres that are home to complex weather systems. Despite their size, these planets spin rapidly, generating high winds that wrap cloud systems into bands parallel to their equator.

Beneath the active atmospheres of Jupiter and Saturn, pressure from above forces hydrogen into a liquid state, and can even break it down into liquid metallic form, generating extremely powerful magnetic fields. The deeper layers of Uranus and Neptune, meanwhile, are composed of icy chemicals in liquid form. Slow contractions of the inner layers due to gravity, coupled with chemical reactions, generate significant heat inside three of the giants, though Uranus is a mysterious exception, helping to power their weather systems even in the cold outer Solar System.

The considerable gravity of the giants puts each one at the centre of its own substantial satellite system – all four are orbited by a mix of 'regular' moons, formed from material left in orbit as the planet itself formed, and 'irregular' objects captured during later close encounters. Each giant also has a ring system of its own, made up of particles trapped in concentric orbits. These vary wildly between the broad, icy planes of Saturn to the tenuous dust around Jupiter and the tightly defined arcs around Uranus and Neptune.

DWARF PLANETS

The term 'dwarf planet' was introduced to clarify the organisation of the Solar System in 2006 – though some might say it's made matters more confusing. Dwarf planets are worlds in orbit around the Sun with sufficient gravity to pull themselves into a spherical shape, but not enough to deflect the paths of other nearby bodies and 'clear their orbits'.

The first dwarfs to be discovered were Ceres in 1801 and Pluto in 1930. Both were originally treated as new major planets, despite their small size, but Ceres was reclassified as an asteroid once more of its neighbours in the main asteroid belt were discovered. Pluto's status became doubtful in the 1990s as more small bodies in similar orbits were found in the Kuiper Belt, but matters came to a head with the discovery of Eris, another 'trans-Neptunian object' of similar size, in 2003.

Source: Wikipedia Commons © Justin Cowart

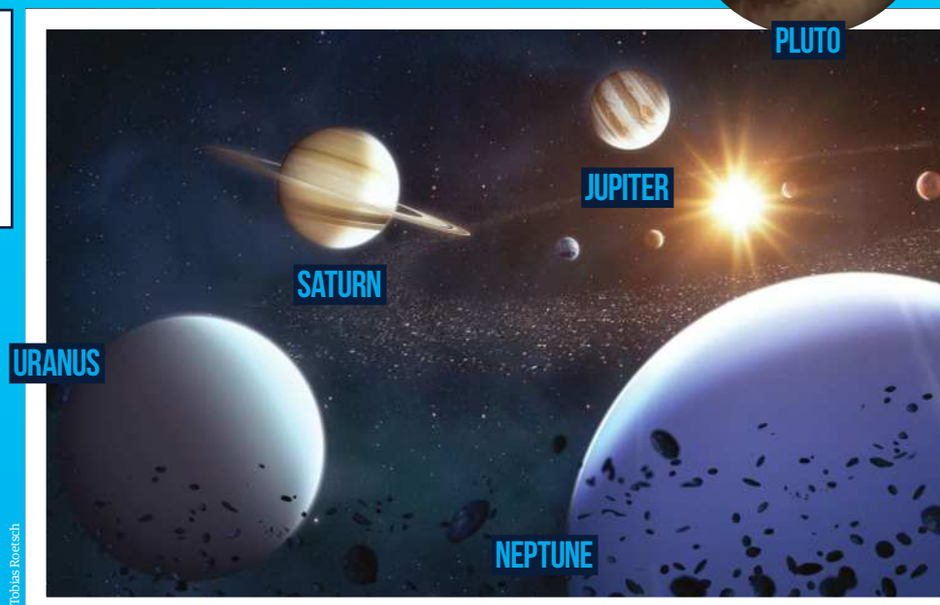
Faced with a potentially ballooning list of 'major' planets, astronomers opted to introduce the new category, demoting Pluto, but sweeping up Ceres into the bargain. Because dwarf planets are classified in part by their shape, and this is still uncertain for some distant worlds, there are still fierce debates about which objects qualify. The International Astronomical Union currently recognises just five: Ceres, Pluto, Haumea, Makemake and Eris.

ROCKY DEBRIS

Although the formation of the Solar System left plenty of rock and dust scattered across the inner Solar System, most of the smaller rocky objects that survive today are confined to the asteroid belt between Mars and Jupiter, where the giant planet's gravity and early shifts in its orbit disrupted any potential for the formation of a fifth rocky planet. Today's asteroid belt contains around 1.5 million asteroids more than one kilometre (0.6 miles) across, along with countless smaller objects.

Although they're scattered across such a vast volume of space that crossing the belt is easy, collisions and close

RIGHT: Beyond the asteroid belt, the planets are gaseous and gigantic in comparison to Earth



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LIFE IN THE SOLAR SYSTEM

Could there be life outside of Earth?

Earth's abundant life is due to its unique position in the Solar System near the inner edge of our Solar System's 'Goldilocks zone', where temperatures are neither too hot nor too cold, but 'just right' for liquid water to survive on a planet's surface. Water is widely seen as a key requirement for life because it's the most abundant and effective 'solvent' that we know of – a chemical within which other molecules can dissolve and move around, permitting the encounters and reactions that are needed for life to evolve and survive. Mars is the only other planet technically just within the Goldilocks zone, and its warmer, wetter history makes it an intriguing destination in the search for past or present extraterrestrial life, but there are also surprising possibilities farther from the Sun. Several large satellites and dwarf planets seem to have liquid-water layers deep in their interiors, while tidal forces raised by Jupiter and Saturn on their icy moons Europa and Enceladus pummel and heat their interiors so much that they have substantial liquid-water oceans just below the surface. Fed with chemical nutrients by undersea volcanoes, these two worlds are seen as the Solar System's most likely spots for alien life to exist.

© Alamy

ABOVE: There are millions of tiny icy and rocky fragments floating through space

BELOW: 'Oumuamua was identified as an interstellar interloper passing through our Solar System

encounters are inevitable on a longer timescale. These lead to the formation of asteroid families with similar compositions and orbits that can be traced back to a common origin. Asteroids vary in composition from 'carbonaceous' objects that have barely altered since the birth of the Solar System to bodies rich in silicate minerals or even iron – fragments of larger ancient worlds that had begun to develop an internal structure before they were smashed apart.

Collisions can also send asteroids onto elliptical orbits that cross over those of the inner planets, with some becoming potentially hazardous near-Earth objects, or NEOs. However, NEO orbits are inevitably unstable over long timescales – ending either in a collision with a major planet or more likely deflection from a close encounter – and so this supply must be steadily renewed.

ICY WANDERERS

The farther out we look in the Solar System, the more volatile ices – not just water ice, but also frozen methane and other compounds – become mixed with the rocky components of solid bodies. This trend is already apparent fairly close to the Sun in the asteroid belt, but it becomes more pronounced among the moons of the giant planets, and above all in the small worlds of the Kuiper Belt beyond Neptune.

The most familiar icy objects, however, are comets. These icy wanderers spend most of their lives in a deep-frozen state, orbiting among the Kuiper Belt objects or even farther out in the Oort Cloud – a vast, spherical comet cloud that surrounds the Solar System. However, they spark into life when chance puts them on an elliptical orbit that brings them close to the Sun. As the comet's solid nucleus warms up, gases evaporating from the surface first form a vast, diffuse atmosphere, called a 'coma', and then an elongated tail that is caught up on the solar wind and dragged away from the Sun.

Comets that visit the inner Solar System may follow orbits that vary from just a few years to tens of thousands. However, each successive visit strips away some of their ice until they eventually become dark, dormant and – depending on their orbits – barely distinguishable from asteroids.

TESTING THE LIMITS

Many astronomers from across the world define the Solar System's outer limit as the boundary where the Sun ceases to be the exclusive dominant influence over nearby objects. According to this definition, the edge of the Solar System lies at the heliopause – the wall where the solar wind streaming out from the Sun comes to a halt in the face of pressure from countless other stellar winds and the 'interstellar medium' – clouds of sparse gas that lie between the stars.

This boundary lies around four times farther from the Sun than Neptune, or 120 times farther out than Earth. Four spacecraft – Pioneers 10 and 11 and Voyagers 1 and 2 – have crossed it so far, and the two Voyagers continue to send back data about conditions on the other side.

Despite the widespread adoption of the heliopause as the formal 'edge' of the Solar System, there are many objects in the space beyond it that still orbit the Sun. Most of these lie within either the scattered disc, a broad outer extension of the Kuiper Belt, or the Oort Cloud. According to the most generous definition, the Solar System extends to the edge of the Oort Cloud, roughly a light year from the Sun.

ESO

"THESE ICY WANDERERS SPEND MOST OF THEIR LIVES IN A DEEP-FROZEN STATE"

THE EIGHT MAJOR PLANETS

MERCURY

Diameter: 4,879 kilometres (3,032 miles)

Mass: 0.055 Earths

Distance from the Sun: 46 to 69.8 million kilometres (28.6 to 43.4 million miles)

Orbital period: 88 days

Rotation period: 58.65 days

Axial tilt: 0.03 degrees

Satellites: Zero

VENUS

Diameter: 12,104 kilometres (7,521 miles)

Mass: 0.815 Earths

Distance from the Sun: 107.5 to 108.9 million kilometres (66.8 to 67.7 million miles)

Orbital period: 224.7 days

Rotation period: 243.02 days

Axial tilt: 177.36 degrees

Satellites: Zero

EARTH

Diameter: 12,742 kilometres (7,918 miles)

Mass: 5.97 billion trillion tonnes

Distance from the Sun: 147.1 to 152.1 million kilometres (91.4 to 94.5 million miles)

Orbital period: 365.256 days

Rotation period: 23 hours and 56 minutes

Axial tilt: 23.44 degrees

Satellites: One

MARS

Diameter: 6,779 kilometres (4,212 miles)

Mass: 0.107 Earths

Distance from the Sun: 206.7 to 249.2 million kilometres (128.4 to 154.8 million miles)

Orbital period: 686.98 days

Rotation period: 24 hours and 37 minutes

Axial tilt: 25.19 degrees

Satellites: Two

JUPITER

Diameter: 139,822 kilometres (86,881 miles)

Mass: 317.8 Earths

Distance from the Sun: 740.5 to 816.6 million kilometres (460 to 506.4 million miles)

Orbital period: 11.86 years

Rotation period: 9 hours and 55 minutes

Axial tilt: 3.13 degrees

Known satellites: 79

SATURN

Diameter: 116,464 kilometres (72,367 miles)

Mass: 95.2 Earths

Distance from the Sun: 1.35 to 1.51 billion kilometres (838 to 938 million miles)

Orbital period: 29.46 years

Rotation period: 10 hours and 34 minutes

Axial tilt: 26.73 degrees

Known satellites: 82

URANUS

Diameter: 50,724 kilometres (31,518 miles)

Mass: 14.5 Earths

Distance from the Sun: 2.74 to 3.01 billion kilometres (1.7 to 1.87 billion miles)

Orbital period: 84.02 years

Rotation period: 17 hours and 14 minutes

Axial tilt: 97.77 degrees

Known satellites: 27

NEPTUNE

Diameter: 49,244 kilometres (30,598 miles)

Mass: 17.1 Earths

Distance from the Sun: 4.44 to 4.54 billion kilometres (2.76 to 2.82 billion miles)

Orbital period: 164.8 years

Rotation period: 16 hours and 7 minutes

Axial tilt: 28.32 degrees

Known satellites: 14

SUN

Diameter of photosphere: 1.39 million kilometres (863,706 miles)

Mass: Around 330,000 Earths

Rotation period: 25 days at equator, 34.4 days at the poles

OUR SUN IS

GETTING HOTTER

AS OUR NEAREST STAR ENTERS ITS NEXT SOLAR CYCLE, PHYSICISTS HAVE REVEALED WHAT THE FUTURE HOLDS – AND IT'S NOT WHAT THEY EXPECTED

OUR SUN IS GETTING HOTTER

As a life-giver that warms and lights up our world, it is easy to forget the true, violent nature of the Sun. As the Sun enters a new cycle of surface activity, we are only now beginning to fully appreciate the wide-ranging ways our star's changeable nature can impact our planet and modern lives.

Solar weather describes the influence of the Sun on the Earth-space environment. Back in 2011, it was added to the UK government's National Risk Register and placed on a similar level to the emergence of a new disease due to the number of people it could potentially impact on Earth.

"The Sun is very dynamic," says Helen O'Brien, lead engineer on the European Space Agency's Solar Orbiter mission. "It has different moods, it is very explosive and it has the potential to damage our modern infrastructure." As well as providing heat and light, our star is constantly throwing out more deadly material. The solar wind is the name given to this constant stream of energised, charged particles, primarily electrons and protons.

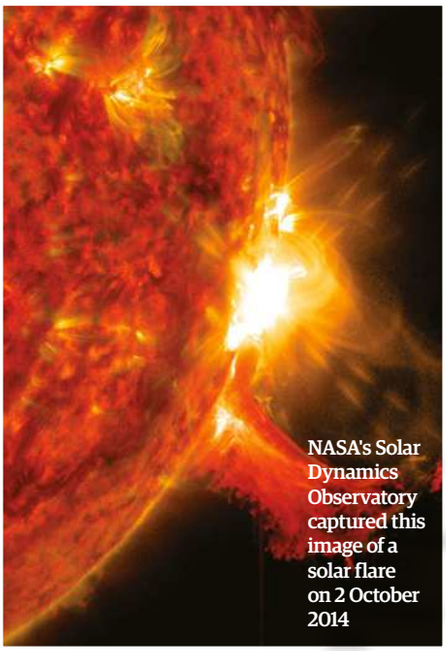
On Earth we are shielded by our planet's magnetic field while high-energy X-rays and ultraviolet light are absorbed high up in the atmosphere. They electrify their surroundings to create the Earth's ionosphere and simultaneously excite constituents of our own atmosphere so they glow and create the famous aurorae.

> "[THE SUN] IS VERY EXPLOSIVE AND HAS THE POTENTIAL TO DAMAGE OUR MODERN INFRASTRUCTURE"
>
> HELEN O'BRIEN

While the aurorae are harmlessly enjoyed by polar communities and tourists, the Sun's own magnetic field can throw far more violent eruptions our way. Its much larger field is composed of a series of magnetic lines that connect distant points on the surface. Over time, these lines can become twisted as the Sun's compositional fluidity sees material at its equator rotate faster than at its poles, and the magnetic field gets wrapped around the star. "When you distort a magnetic field it is like stretching an elastic band," highlights Chris Scott, professor of Space and Atmospheric Physics at the University of Reading. "You are storing up energy."

Those magnetic distortions cause complex knots to form, which burst to the surface as sunspots. When the Sun is very active you have lots of energy stored up in these knots, and occasionally the system will reconfigure itself through solar flares that throw out vast quantities of high-energy plasma like a cloud from the Sun's atmosphere.

These eruptions can be incredibly violent. The largest – known as coronal mass ejections, can contain billions of tonnes of material – which



NASA's Solar Dynamics Observatory captured this image of a solar flare on 2 October 2014

travels out from the Sun at speeds of several million miles per hour.

If Earth is in the crosshair of these large storms the consequences can be both spectacular and costly. This was evident even back in September 1859 on the night of the most famous direct hit, known as the 'Carrington Event', which bathed almost the entire surface of the Earth in beautiful aurorae. Though the Carrington Event was spectacular in its scale and spectacle, it was also the first example of solar weather impacting our technology – recently rolled out telegraph systems in America and Europe were hit by fires and gave people electric shocks.

In today's age of integrated power networks and satellite communications, a similar strike today could bring down radio communications and upset electronics on the ground, causing long-distance power grids to fail. In 1989, a coronal mass ejection blacked out the entire Canadian province of Quebec, while a more recent economic risk assessment by researchers from the University of Oxford found that a Carrington-style event could leave the UK with £15.9 billion (approximately $20.5 billion) worth of damage.

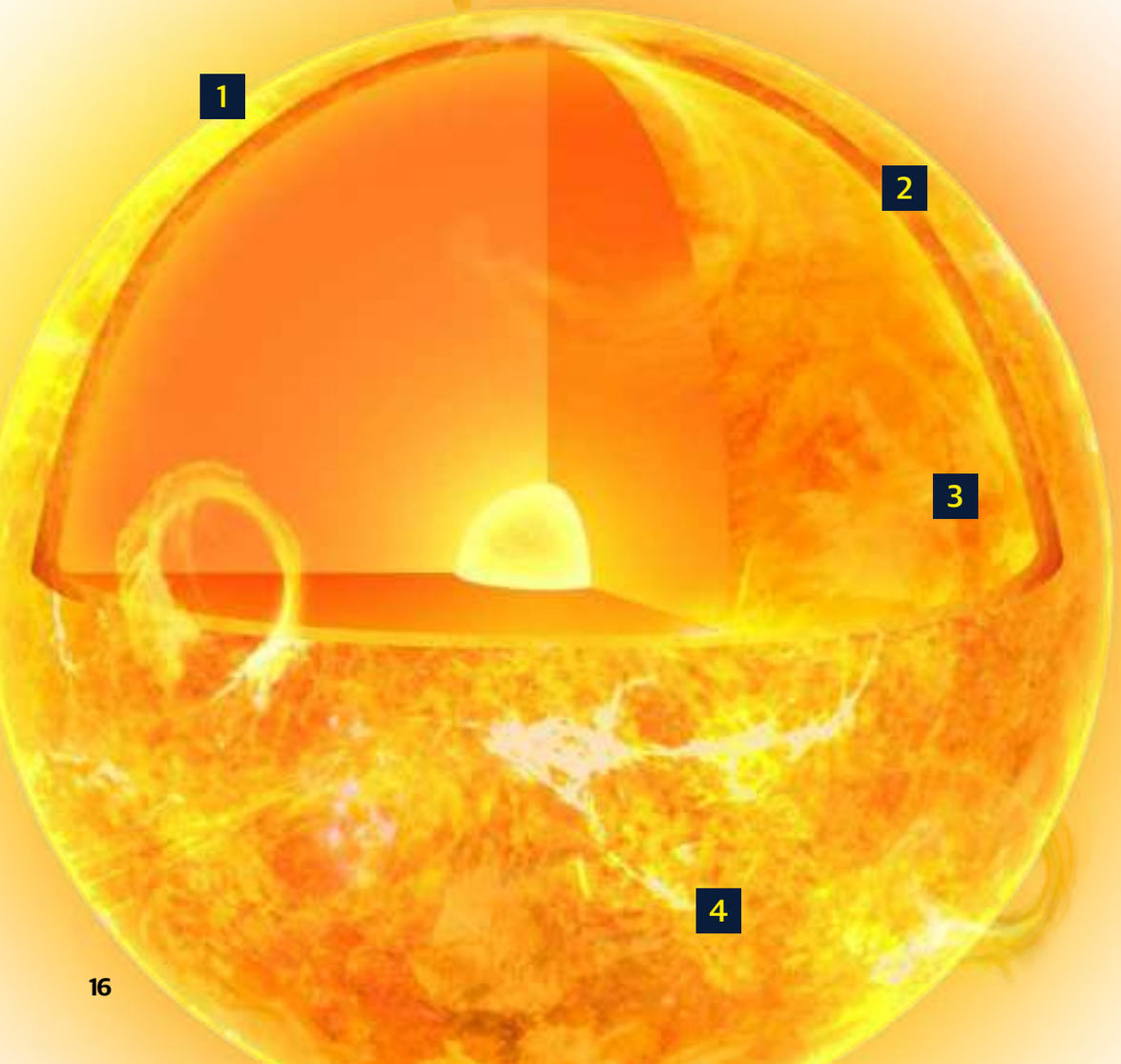
In general, a direct threat to human life on the Earth's surface is low. However, a small proportion of our population is spending more and more time higher up, and that does create risks. Storms increase the radiation impacting spacecraft to levels that could threaten astronaut health, while more transatlantic flights are crossing the poles where solar wind material is constantly funnelled by Earth's magnetic field.

Exposure from a single flight during normal solar conditions will be tiny, but there is concern

"A STRIKE TODAY COULD BRING DOWN RADIO COMMUNICATIONS AND UPSET ELECTRONICS ON THE GROUND, CAUSING POWER GRIDS TO FAIL"

WHAT'S GOING TO HAPPEN TO THE SUN?

Each layer of our home star is affected in the cycle change



1 SUN'S MAGNETIC FIELD

The magnetic field transitions from a simple arrangement at solar minimum to a complex tangled web as it wraps around the Sun, though recent cycles have not produced the same intensity of maximum.

2 CORONA

Though generally marked by lower output, solar minimums can still see heightened periods of high-energy particles released from this upper-atmospheric layer as the Sun's magnetic field creates holes in the corona. However, it's during the solar maximum when the corona will be most active, full of spinning tornados, nanoflares and looped-shaped helmet streamers. As you move towards solar maximum, solar flares push more frequently through the corona, heating its gas up.

3 PHOTOSPHERE

On the surface of the lowest layer of the Sun's atmosphere, the start of a new cycle is marked by the appearance of sunspots in higher latitudes. Solar flares also become much more common as you approach solar maximum.

4 CHROMOSPHERE

The second of the Sun's three atmospheric layers experiences frequent heating by ascending solar flares as you approach the solar maximum. Solar prominences, gigantic plumes of gas rising up from the photosphere, are also more abundant at solar maximum and during louder solar cycles. As are spicules, jet eruptions of gas that shoot upwards and outwards into the corona.

THE SUN'S EFFECT ON THE PLANETS

Whether stripping them away or lighting them up, the atmospheres of the Solar System's worlds are continually shaped by the output of our star

1 VENUS

Without its own magnetic field, lighter gases from Venus' thick atmosphere, including water vapour, are continuously blown away by the solar wind, creating an ionosphere that resembles a comet's tail emanating from its night side.

2 MERCURY

Mercury's close proximity to the Sun and lack of atmosphere leaves its relativity weak magnetic field swamped by solar eruptions and its surface bathed in the radiation of the solar wind.

3 MARS

Mars' diminutive size and weak gravitational hold left it unable to cling onto its early thick atmosphere as its own magnetic field was lost when its molten interior cooled and solidified. It was subsequently stripped away over time by the solar wind.

4 JUPITER

Recent data from NASA's Juno spacecraft suggests Jupiter's powerful blue aurorae are not entirely powered by the same solar wind mechanism behind aurorae on the other planets. Can the largest planet in our Solar System generate its own?

5 SATURN

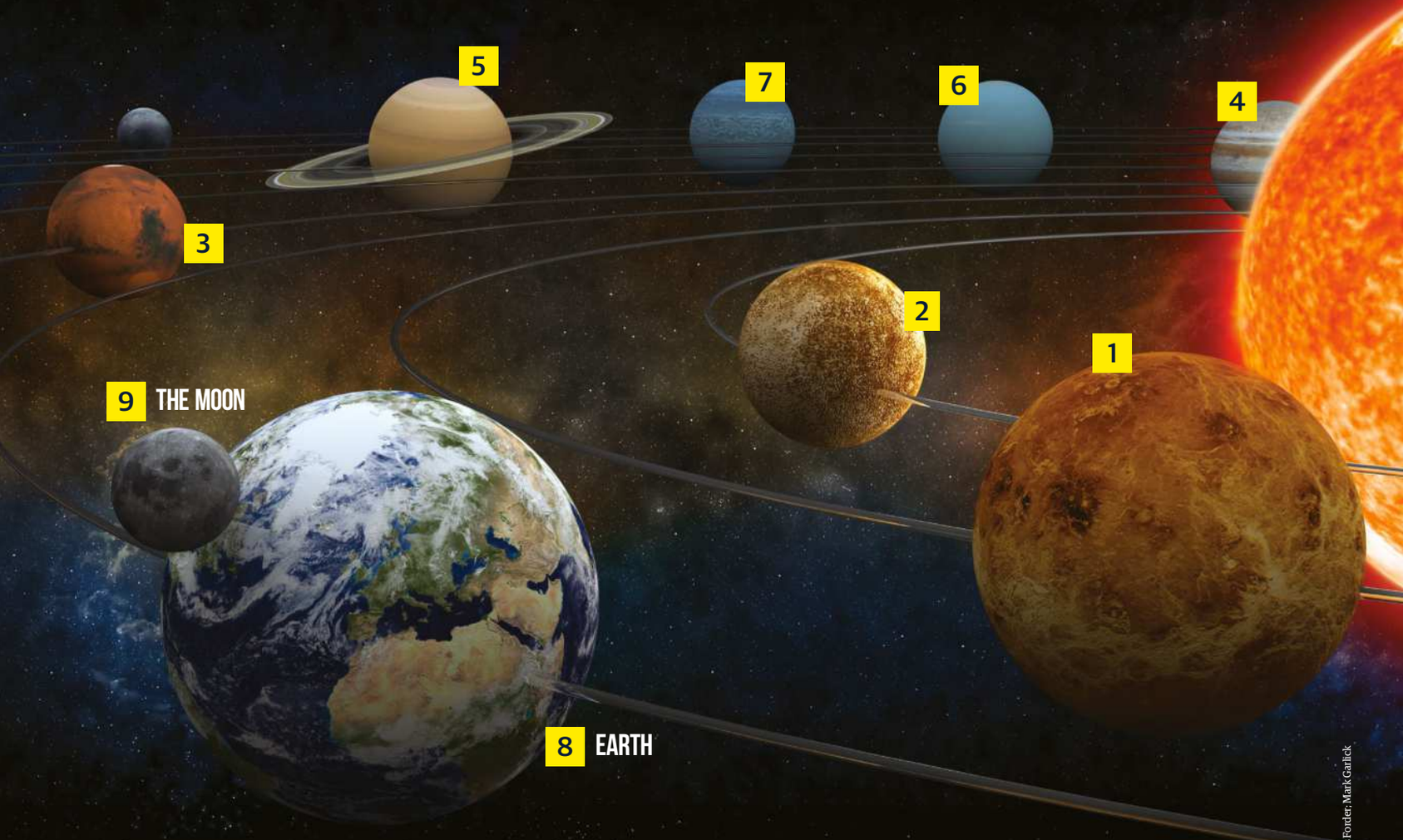
Above and below its ringed equator, Saturn's poles are regularly lit up by strong aurorae, though as they are in the UV and infrared part of the spectrum they would be invisible to us. However, weaker aurorae of pinky-purple visible light have been observed.

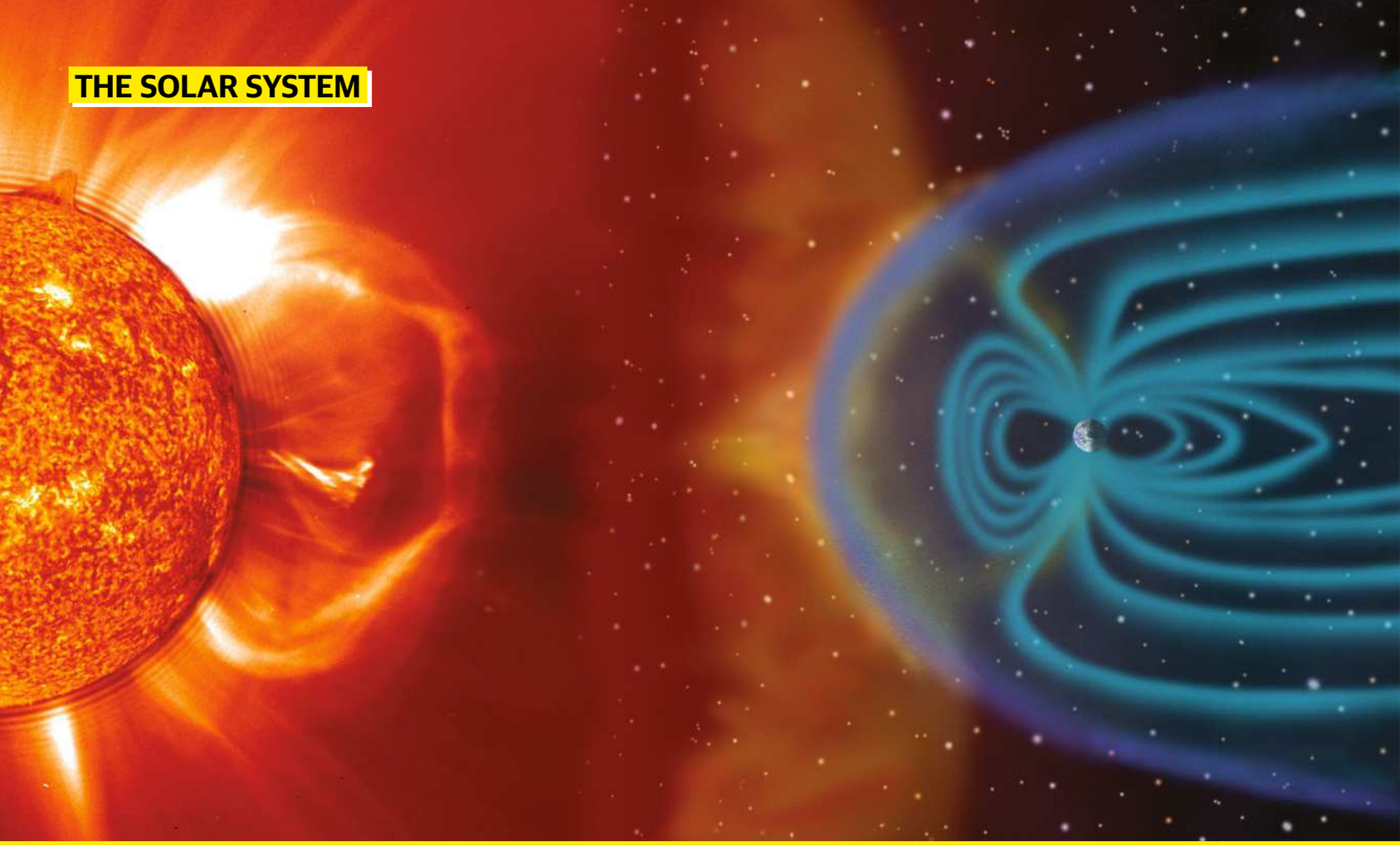
6 URANUS

On Uranus, the solar wind excites atmospheric hydrogen to create its aurorae, which can be found close to its geographical – though not geomagnetic – equator, as the planet orbits on its side.

7 NEPTUNE

Aurorae were spotted on Neptune by the Voyager 2 flyby in the 1990s. However, the distinct offset between the planet's magnetic field and its rotational axis means these weak light displays can be found across the surface.





for flight staff working up there year round. Also, recent research from Clive Dyer of the University of Surrey Space Centre suggests flying in modern aircraft during a solar storm could expose passengers to radiation levels equivalent to the annual working limit for air crews. This threat has left satellite companies, aircraft operators and power companies carefully monitoring the solar cycle for clues as to when the threat level will be at its highest.

By counting sunspots on the Sun's surface scientists have for some time known of 11-year cycles of increasing and decreasing solar activity and surface eruptions, driven by the tangling and untangling of the magnetic field lines. These plots indicate we are approaching the latest solar minimum, and therefore entering a new cycle.

Recent magnetic field evolution models developed by the Center of Excellence in Space Sciences in India concluded that the solar maximum of the next cycle, solar cycle 25, will occur around 2024. They also suggested the cycle could buck a wider trend of decreasing solar maximum intensities since the early 1990s, though perhaps not in a way that would greatly threaten ground or space-based infrastructure.

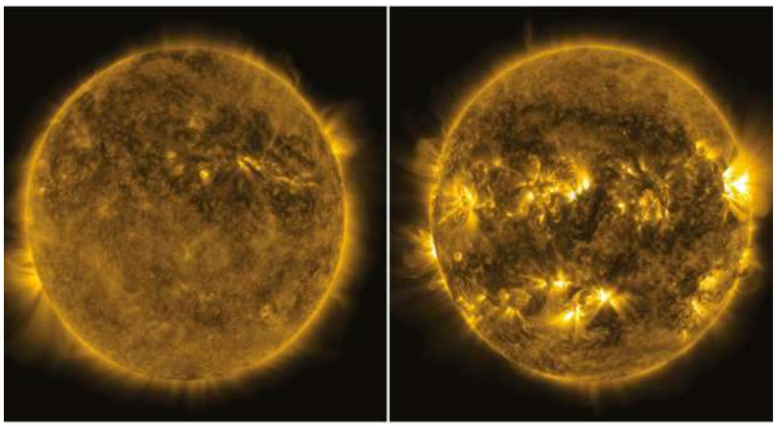
"It is unlikely that this will affect big solar storms, as these can happen at any stage of the solar cycle," explains Scott. However, anticipating the timing and severity of the coming solar cycle could help us prepare for the more local effects such solar variability that effect our lives and which have only come to light in the last decade or two.

Researcher Pablo Mauas has published a series of papers analysing river flows of the Paraná River, as well as measuring snow accumulation and counting tree rings to establish a remarkable agreement between local precipitation rates and the number of sunspots, tracked back over many decades. "I can quite believe there is an 11-year cycle in the flow rates of the river," says Scott, who points to evidence of similar solar-influenced systems closer to home.

During recent low periods of solar activity it seems the jet streams become more meandering, and you get more 'blocking events' where air-pressure systems get stuck over a certain location. These phenomena are thought to account for some of the very cold recent winters in northwest Europe, but perhaps this trend may reverse slightly if the next solar cycle is more active, as the Indian research team suggests.

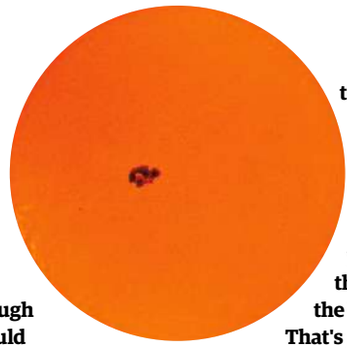
In his own research, Scott has shown that fast jets of solar wind passing the Earth, associated with more active solar periods, can result in a substantial increase in lightning strikes across Europe for up to 40 days as a result of disturbances to the electrical properties of the atmosphere. While communities and populations may need to adapt to changes in these localised weather systems, a better way of predicting larger scale solar weather on a more detailed day-to-day basis is an urgent priority.

This becomes more pressing if Carrington events prove to be more common than that 'once-in-a-century' tag. Reanalysis of magnetic behaviour measurements in the Earth's atmosphere by Scott's colleague Mike Lockwood has found storms in 1941 and 1972 that may have been as big, if not bigger, than Carrington, but had surprisingly little impact. "It might be that the biggest parts occurred over parts of the world where there wasn't the technological



ABOVE: A CME blasting from the Sun's surface in the direction of Earth

LEFT: The Sun goes through a natural solar cycle every 11 years, composed of significant increases and decreases in sunspots and eruptions



infrastructure to be disturbed," says Scott.

There was also a storm in July 2012 that narrowly missed the Earth and fortunately hit a solar-observation spacecraft from the Solar TErrestrial RElations Observatory (STEREO) mission. It was travelling fast enough that if it had been on target, it would have triggered a modern-day Carrington-like event. If we are not to be so fortunate during the next solar cycle, we will need to investigate ways to provide more detailed forecasts of what is coming at us.

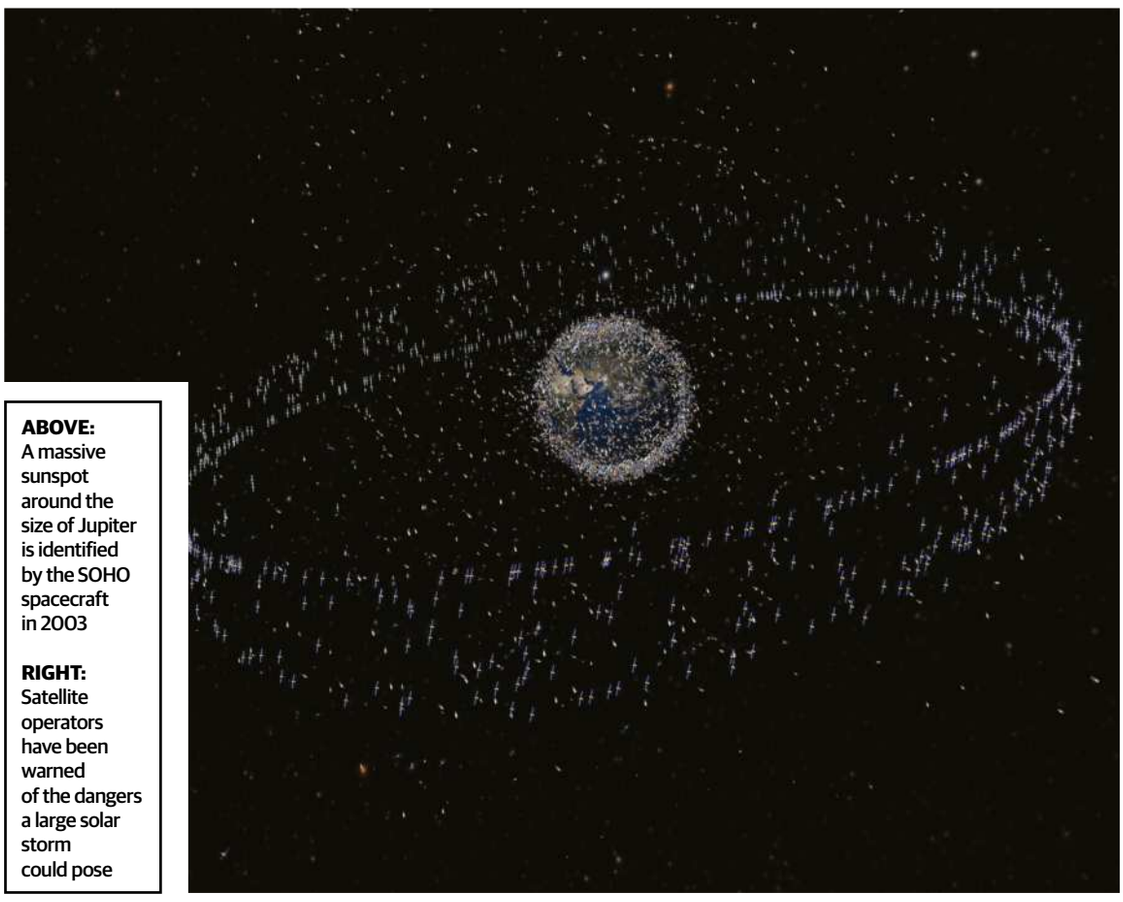
"It's like on Earth; we can say the winter will be colder than the summer and we will get more rain," says O'Brien. "But what you really want to know is if it is going to rain on the day of your party." However, there are challenges replicating our ability to predict Earth weather in space.

Meteorologists utilise a vast network of monitors collecting data 24/7 as satellites constantly track weather systems from above in order to run their increasingly sophisticated simulations. And while we have models of the solar wind and how it propagates through space and interacts with the Earth, we can't look down on the entire system as we can when tracking tropical storms or rain fronts. "Imagine yourself as a meteorologist back in the pre-space age in the 1950s, and you are trying to make sense of all these spot measurements without the benefits of a satellite picture. That's probably where we are with space weather," says Scott.

Reliable space weather forecasts will also require a greater understanding of the relationship between what we see on the Sun's surface and what is in line to hit us several hours or days later. To help in this endeavour we have sent up a community of craft to monitor the Sun. However, they are all primarily scientific missions sent up to answer scientific questions. "They are proving useful, but they are not optimal," says Scott, whose STEREO mission can only provide data at the end of each day, which isn't much use when really powerful, fast-moving storms can get to Earth in 17 hours.

The scientific community are in regular contact with industry and space agencies who are working to ensure that they have spares at the most vulnerable parts of their grids, safe

"A LOT OF SATELLITE OPERATORS CHOOSE NOT TO WORRY ABOUT FORECASTS BECAUSE THEY DO NOT HAVE SUFFICIENT ACCURACY" PROFESSOR CHRIS SCOTT



ABOVE: A massive sunspot around the size of Jupiter is identified by the SOHO spacecraft in 2003

RIGHT: Satellite operators have been warned of the dangers a large solar storm could pose

WHAT IF OUR SUN BECAME TOO ACTIVE?

With enough notice and preparedness we could negate the dangers and simply enjoy the greatest light show of all time

ALL EYES TO THE SKIES

If major solar activity were to threaten Earth, our solar science community and their legion of orbiters as well as land-based observatories would need to work out the likelihood, scale and arrival date of a direct hit.

PLANES TAKE THE LONG WAY AROUND

To avoid endangering staff and passengers with exposure to high radiation levels, operators of transatlantic flights would be encouraged to avoid usual 'over the poles' routes.

ASTRONAUTS TAKE REFUGE

During an intense solar storm any planned spacewalks are cancelled and astronauts would be asked to set themselves up in the most shielded modules of the station.

SATELLITES SWITCHED TO SAFE MODE

If given sufficient notice of an incoming solar storm satellite operators would be encouraged to switch any orbiting units to safe mode.

SAVING POWER

To avoid blackouts, power companies will need significant stocks of replacement transistors and crew deployed on the ground to tend to damaged parts of their grids.

THE GREATEST LIGHT SHOW ON EARTH

One positive effect of intense solar activity is the chance for more people to enjoy the northern and southern lights at much lower latitudes than usual are bathed in aurorae.

SOLAR SURVEYORS

To better understand solar weather, space agencies have sent up a family of orbiters, satellites and probes.

SOLAR SURVEYORS

To better understand and anticipate solar weather, space agencies have sent up a family of orbiters and satellites

1 PARKER SOLAR PROBE

The mission to 'touch' the Sun, this probe is the first man-made object to get within 6 million kilometres (4 million miles) of the Sun's surface. At that distance it measures the pristine solar wind up close before the 'outburst' gets jumbled up in the journey towards Earth.

RESULTS: Full report pending

2 SOLAR ORBITER

Launched in 2020, it hopes combines solar wind particle and magnetic field measurements with direct surface observation. It will monitor the Sun on highly elliptical orbits which will allow it to spend 10 to 15 days co-rotating with the Sun, providing uninterrupted coverage of sunspot, flare and storm development.

RESULTS: Full report pending

3 ACE

Launched back in 1997 to study the energetic particles from the solar wind, as well as providing the NOAA Space Weather Prediction Center with data for forecasts and warnings of solar storms.

RESULTS: Discovered that the current solar cycle, as measured by sunspots and coronal mass ejections, has been much less magnetically active than the previous cycle.

4 IBEX

A NASA satellite launched in 2008 that aimed to map the boundary between the Solar System and interstellar space.

RESULTS: In 2013, IBEX results revealed the Sun's heliosphere has a tail.

5 WIND

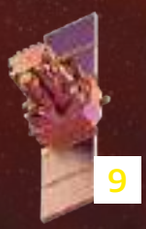
A NASA science spacecraft launched in 1994 to study radio waves and plasma that occur in the solar wind and in the Earth's magnetosphere.

RESULTS: Researchers have found evidence for a type of plasma wave moving faster than theory predicted within the solar wind using Wind data. The research suggests that a different process than expected may be driving the waves.

6 IRIS

A NASA satellite launched in 2013 to Investigate the physical conditions at the very edge of the Sun's visible disc – known as the solar limb. In particular it has looked at the chromosphere layer, whose rosy-red colour is only usually visible to us on Earth during eclipses.

RESULTS: IRIS has shown that the interface region of the Sun is significantly more complex than previously thought and includes features described as solar heat bombs, high-speed plasma jets, nano-flares and mini-tornadoes.



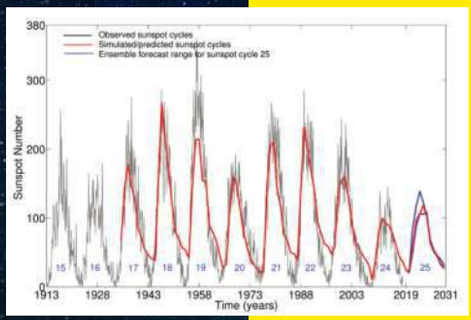
7 HINODE

A Japan Aerospace Exploration Agency-led satellite whose Sun-synchronous orbit over the day/night terminator allows near-continuous observation to explore the magnetic fields of the Sun.

RESULTS: In 2018, astronomers using the Hinode spacecraft observed the strongest magnetic field ever directly measured on the surface of the Sun.

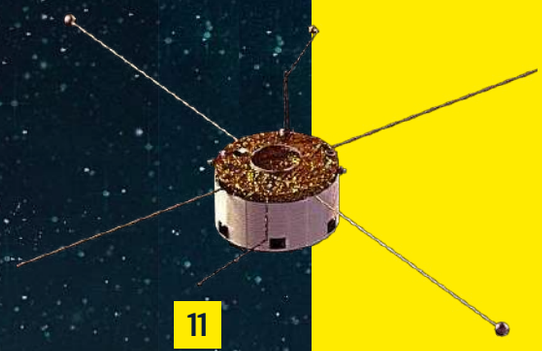
8 STEREO

Two near-identical spacecraft launched in 2006 into orbits around the Sun ahead of and behind the orbit of the Earth. This enables stereoscopic imaging to provide in-depth information when observing solar phenomena, such as coronal mass ejections.
RESULTS: One of the STEREO craft – STEREO A – was in the path of the solar storm of 2012 which was similar in strength to the Carrington Event. Its instrumentation was able to collect and relay a significant amount of data about the event.



9 SOHO

One of the original craft still in operation, SOHO was launched in 1995 and combines imagers and spectrometry instruments to probe the layered structure of the Sun with in-situ measurements of the solar wind as it goes past.
RESULTS: SOHO has also discovered over 3,400 comets as they orbit around the Sun, as well as providing the main source of near-real-time solar data for space weather prediction.



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10 SOLAR DYNAMICS OBSERVATORY

Launched in 2010 to investigate how the Sun's magnetic field is generated and structured and how this stored magnetic energy is converted and released into the heliosphere in the form of solar wind, energetic particles and variations in the solar irradiance.
RESULTS: Has identified possible precursors to space weather in the behaviour of plasma within the regions encircling sunspots.

11 CLUSTER II

Launched in 2000, the Cluster II mission is an in-situ investigation of the interaction between the solar wind and the magnetosphere by using four satellites.
RESULTS: Has developed the first models of the Earth's magnetic field and its interaction with the solar wind based on actual measurements rather than theory.

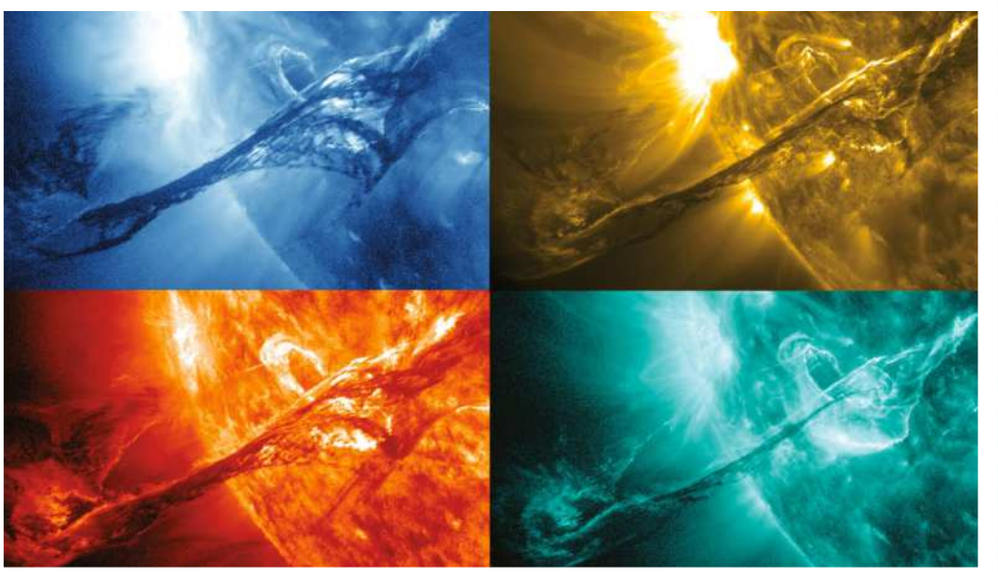
ABOVE: Researchers have modelled the number of sunspots between 1913 and 2031

BELOW: The coronal mass ejection, viewed in four extreme ultraviolet wavelengths, in 2012 that sent a massive solar storm that just missed Earth

12

12 DSCOVR

Originally proposed by then-Vice President Al Gore, DSCOVR monitors variable solar wind conditions and their impact on the Earth, including changes in ozone, aerosols, dust and volcanic ash, cloud height, vegetation cover and climate.
RESULTS: Took the second picture of the entire Earth, following on from the final Apollo mission's famous Blue Marble picture.



modes for their satellites, back-up routes for transatlantic airlines and safe houses for orbiting astronauts. However, today's rudimentary early warning systems make preparedness a significant economic risk.

"A lot of satellite operators choose not to worry about space weather forecasts because they do not have sufficient accuracy to make it worth their while," highlights Scott, who calls for a new observation-focused mission to put a spacecraft out far enough to see the Sun and the Earth in the same field of view. It would be stationed near enough to us to provide continuous real-time observations.

Further notice could be provided by looking for signature surface behaviour that proceeds major eruptions. This is where two of the latest additions to the Sun's community of human-made companions could prove useful. O'Brien's ESA-funded Solar Orbiter mission is due to launch in 2020. It combines solar wind particle and magnetic field measurements with direct surface observation, all from inside the orbit of Mercury.

Key to the Solar Orbiter's ability to spot impending eruptions will be its highly elliptical orbit, which will allow it to spend ten to 15 days co-rotating with the Sun, providing uninterrupted coverage of sunspot, flare and storm development.

While the Solar Orbiter will take direct solar observation closer than ever before, NASA's Parker Solar Probe is pushing the boundary yet further. On 26 March 2022, the European Space Agency the spacecraft successfully completed its first close pass through the Sun's corona, bringing us closer to the sun than ever before. At that distance it hopes to measure the pristine solar wind – what it looks like when it leaves the Sun before it gets jumbled up in the 150-million-kilometre (93-million-mile) journey to Earth. "We will be able to couple together unprecedented details on what is happening on the dynamic, bubbling, boiling surface of the Sun with what is going in interstellar space," says O'Brien, who believes these new data sets and monitoring stations provide hope for our ability to give fair warning of future eruptions during the next solar cycle.

PLANET PROFILE

MERCURY

THE MINUTE WORLD IS ARGUABLY THE LEAST EXPLORED OF THE FOUR TERRESTRIAL PLANETS

Mercury is a planet that has sculpted not only our scientific understanding over generations, but also our culture. Mercury has been mentioned in texts dating as far back as the 2nd millennium BCE by the Sumerians, and the ancient namesake of the planet is the Roman messenger god, Mercury.

Mercury is the smallest of all the true planets in the Solar System and the closest planet to the Sun, but there is so much more to it. Mercury is so tiny compared to the other planets that you can fit approximately 23,500 Mercurys into Jupiter, and it is roughly 1,400 kilometres (870 miles) larger in diameter than the Moon. The small planet also orbits the Sun with less than half the distance between the Sun and the Earth, resulting in it being 'tidally locked'.

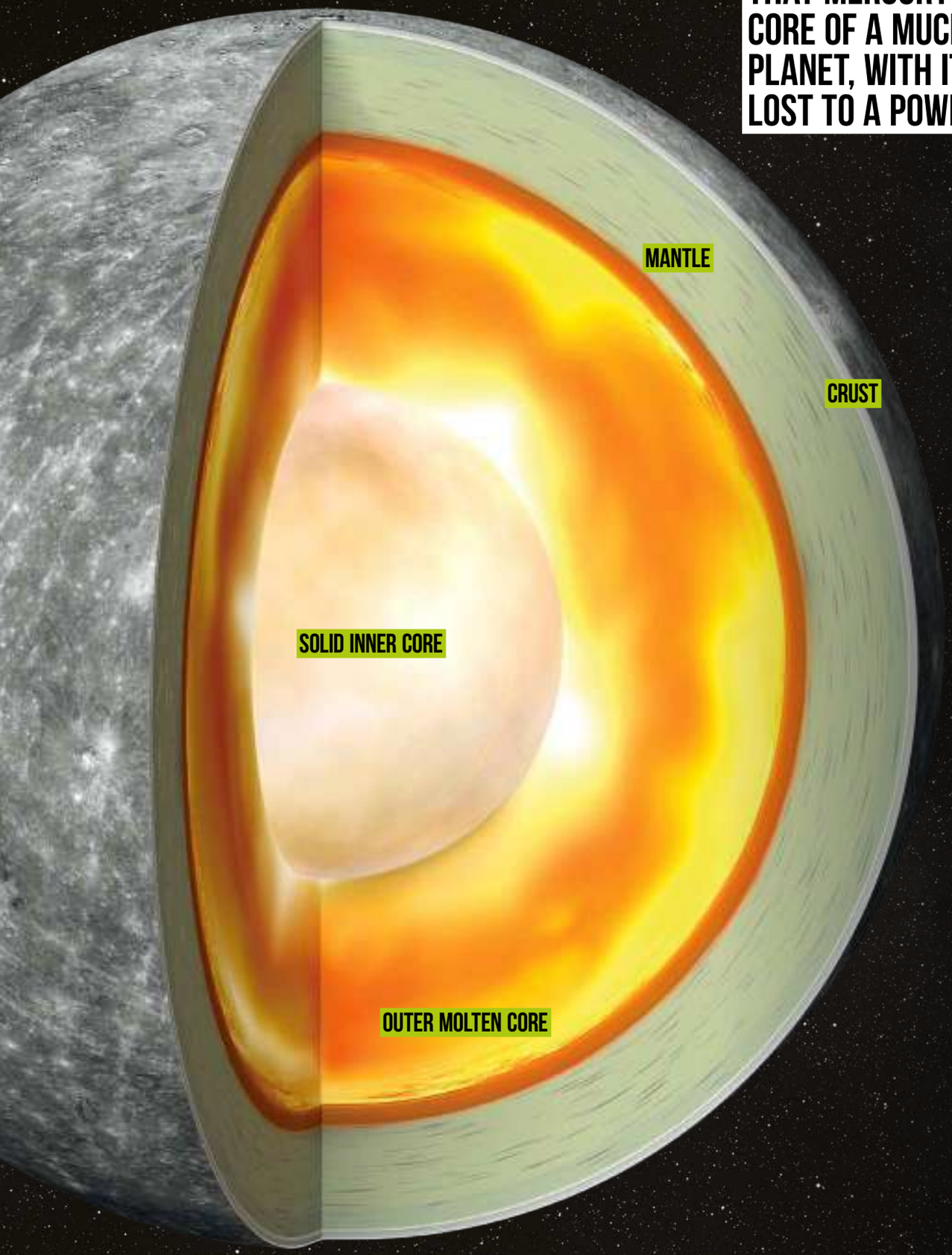
Tidal locking occurs when an object is so close to its host object that the gravity is overwhelmingly powerful, and instead of continuously spinning on its axis, like Earth does, the object has one side facing towards the host object at all times. In this case, Mercury is tidally locked to the Sun, and for every two revolutions around the Sun, Mercury rotates on its axis three times. Each of its orbits takes 88 Earth days, making a year on Mercury roughly a quarter of an Earth year.

Because Mercury is so close to the Sun, its surface temperatures can be scorching, reaching highs of 450 degrees Celsius (840 degrees Fahrenheit). Enduring this bombardment of radiation from the Sun, the planet also struggles to keep hold of its atmosphere, meaning that no heat is trapped. This means the night side of the planet – the one facing away from the Sun – can have temperatures as low as -180 degrees Celsius (-290 degrees Fahrenheit).

While Mercury is a similar size to the Moon, it is also similar in appearance. It is a heavily cratered, rocky body with some of the largest craters in the Solar System. One crater studied by previous exploration missions is a great example. The Caloris basin, which is roughly 1,550 kilometres (960 miles) wide, is about the size of Texas, and was formed when an asteroid about 100 kilometres (60 miles) across hit Mercury's surface 4 billion years ago, impacting the planet with energy equivalent to a trillion one-megaton bombs.

If you scratch beneath the surface, the true weirdness of Mercury starts to become apparent. Under the ultra-thin cratered crust is an extremely dense planet, with somewhere between 70 and 85 per cent of the planet being an enormous iron core. Astronomers have spent years constraining whether it is solid, molten or both, and they seem to agree it has a solid iron core with an outer molten core. Astronomers believe that a molten core could explain Mercury's very weak magnetic field. However, after the results were brought back and analysed from NASA's Mariner 10 and MESSENGER space probes, astronomers now believe that Mercury is the exposed core of a much larger planet, with its outer layers lost to a powerful collision billions of years ago.

"ASTRONOMERS NOW BELIEVE THAT MERCURY IS THE EXPOSED CORE OF A MUCH LARGER PLANET, WITH ITS OUTER LAYERS LOST TO A POWERFUL COLLISION"



ATMOSPHERIC COMPOSITION

42%
OXYGEN

29%
SODIUM

22%
HYDROGEN

6%
HELIUM

0.5%
POTASSIUM

+

TRACES OF ARGON, CARBON DIOXIDE, WATER, NITROGEN, XENON, KRYPTON, NEON, CALCIUM, MAGNESIUM

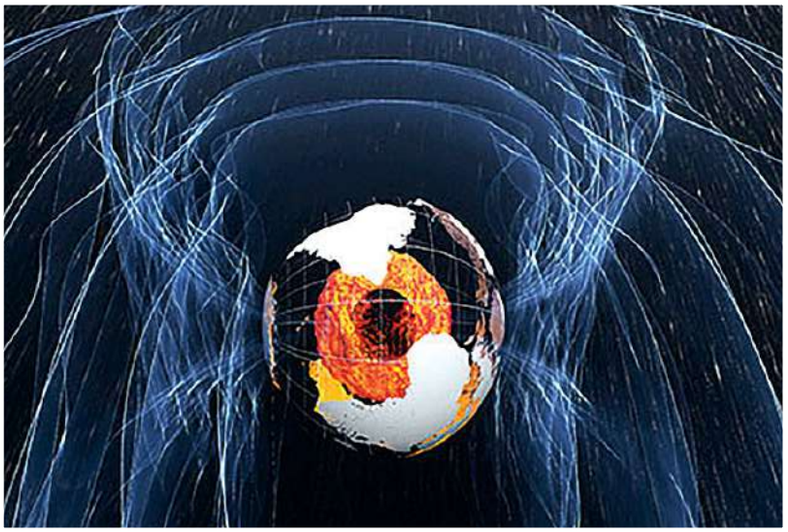
NEWS FROM MERCURY

MERCURY'S MAGNETIC IRREGULARITIES

A magnetic field is the result of the motion of an internal molten core, and that is certainly the case on Earth. Earth's magnetic poles have also been known to shift in location from time to time, but now astronomers have suggested that Mercury's ancient magnetic poles have been doing the same thing.

Mercury's ancient magnetic poles, known as paleopoles, appear to have shifted throughout time, and this could present clues in the investigation of Mercury's interior. By understanding the magnetic field, astronomers could pinpoint the nature of the planet's molten core. "There are several evolution models of the planet, but no one has used the crustal magnetic field to obtain the planet's evolution," says Joana S. Oliveira, an astrophysicist at the European Space Agency's European Space Research and Technology Centre in Noordwijk, the Netherlands.

These results came from NASA's MESSENGER data collected on ancient craters that had irregular magnetic signatures. Not only would a further analysis help us understand the nature of Mercury's interior, but it could also have implications for understanding how the planet evolved, and even how Earth's magnetic field evolved.



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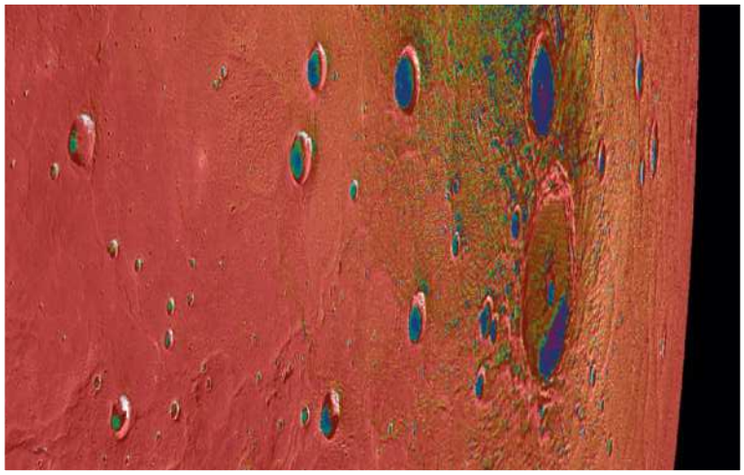

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AN INSULATING BLANKET OF IRON SULPHIDE

Once again Mercury's magnetic field is the centre of astronomers' research. However, instead of trying to understand the nature of it, astronomers are trying to understand how it is kept in place. Astronomers have seen with Mars how a planet much smaller than Earth can solidify and lose its molten core, and consequently lose its magnetic field, but Mercury still appears to have one.

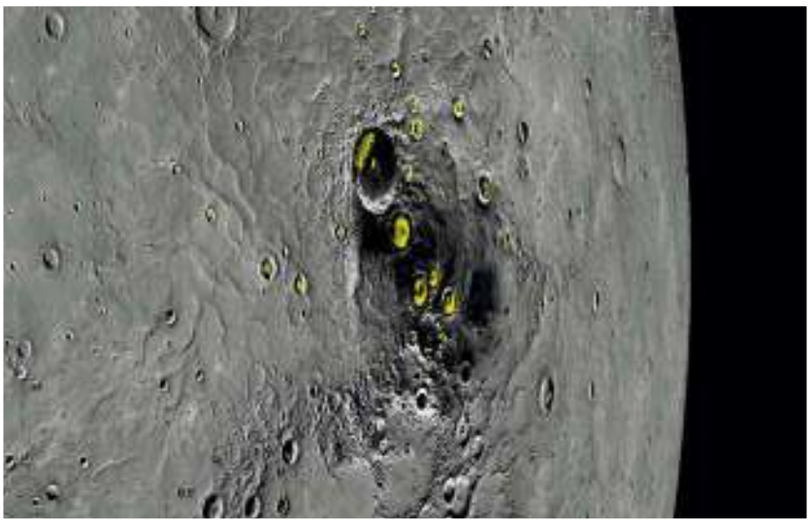
This recent research suggests that a layer of iron sulphide could be insulating Mercury's core, maintaining its molten state. "Based on lab experiments, we got some data to explain how actually you can generate such a low magnetic field and sustain it for such a long time," explains mineral physicist Geeth Manthilake of Clermont Auvergne University in Clermont-Ferrand, France.

These experiments predict that Mercury has a solid inner core, with a molten outer core made up of iron, sulphur and silicon. Much like water and oil, these elements can't mix, so the iron and sulphur compounds were expelled toward the outer regions of the planet and created the insulating layer.

SEARCHING FOR WATER ICE ON MERCURY

The search for water in the Solar System has become more of a hunt among astronomers as engineers and scientists alike keep a keen eye out for its cosmic signature and prepare for a mission to the Moon's poles. Mercury is another body that astronomers suspect is hiding the valuable commodity at its poles, with NASA's MESSENGER probe revealing the signatures of thick deposits of water ice hidden in craters at the planet's poles. In these craters, sunlight doesn't reach the depths within, and they're sheltered from the radiation that could cause water ice to dissipate. Astronomers believe these craters could hold answers about where water is dispersed throughout the Solar System and even the origins of life itself.

Astronomers have also been comparing Mercury and the Moon to understand what the water ice in these craters may look like. This involved looking at about 14,000 craters on the two bodies, over 2,000 of which are on Mercury. They have come to the conclusion that on the Solar System's smallest planet, craters that harbour ice have shallower sides than those that don't.



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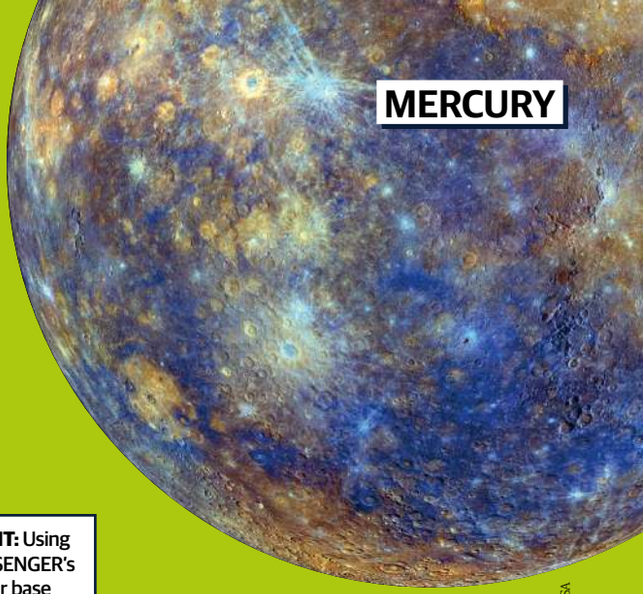

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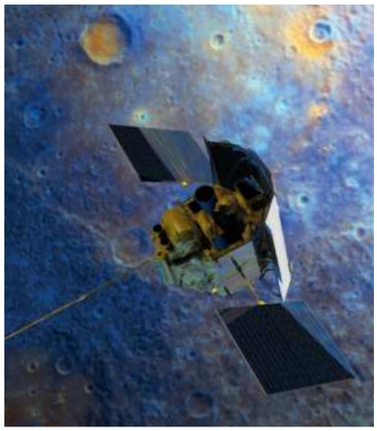
EXPLORING THE PAST AND FUTURE OF THE SWIFT PLANET

Visiting Mercury is a dangerous and difficult task. Some may think that this is because it's a relatively small planet and therefore more difficult to navigate to, but that is far from the case. The voyage to Mercury is difficult because of the humongous ball of searing plasma, the Sun, and its pesky gravity. Navigating a spacecraft to Mercury requires propulsion that will get it to Mercury and also counteract the gravity of the Sun so the craft doesn't go falling into the surface and burn up. This is why only two spacecraft have ever visited the small terrestrial planet.

NASA has been the operator of both of these missions, the first being Mariner 10 in 1974, which conducted a series of flybys and gathered close-up images. However, the mission that brought the most consistent and fascinating results is the MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) spacecraft, which is the first and only spacecraft so far to orbit the planet. MESSENGER's most important results included how volatile-rich the planet was – volatiles being chemical compounds with low boiling points – which has important implications for the planet's formation. Also there were its ice deposits at the poles, its weird magnetic field offset and its irregular depressions called 'hollows'.



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The next mission to Mercury is the exciting BepiColombo, a joint endeavour by the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA). This mission will arrive at Mercury in 2025, where it will separate into two orbiters and use its impressive instrumental suite to investigate the planet from all angles.

The Mercury Planetary Orbiter (MPO) was built and will be operated by the ESA, and the Mercury Magnetospheric Orbiter (Mio) was built and will be operated by JAXA. This unique mission will have its two orbiters working simultaneously as scientists get up-close observations of the surface and far-away monitoring of the magnetic field.

RIGHT: Using MESSENGER's colour base map imaging, Mercury is shown in a colourful contrast

LEFT: MESSENGER spent the best of four fruitful years at Mercury

BELOW: The Van Eyck crater is just one of the many enormous craters on Mercury

BEPICOLOMBO'S SEVEN-YEAR JOURNEY TO MERCURY

- **Date:** 20 October 2018 **Activity:** Launch from Earth
- **Date:** 13 April 2020 **Activity:** Earth flyby
- **Date:** 16 October 2020 **Activity:** First Venus flyby
- **Date:** 11 August 2021 **Activity:** Second Venus flyby
- **Date:** 2 October 2021 **Activity:** First Mercury flyby
- **Date:** 9 January 2025 **Activity:** Sixth Mercury flyby
- **Date:** 5 December 2025 **Activity:** Orbital insertion around Mercury

MERCURY FACTS

0

Mercury has no moons, making it one of two planets in the Solar System – along with Venus – to not have its own moon

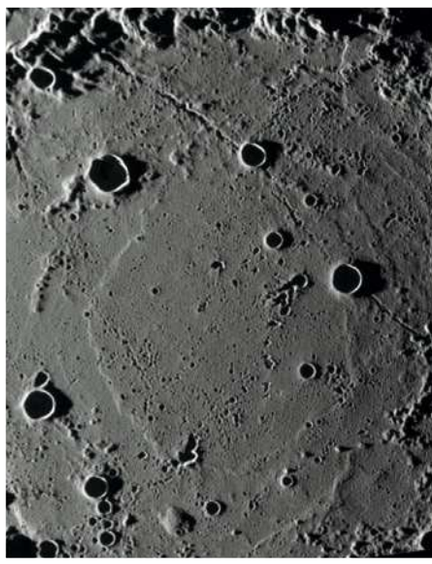
Mercury's atmosphere is more comparable to a 'thin exosphere', as it is comprised mostly of atoms ejected from the surface due to the solar wind and meteoroid impacts

If someone was standing on Mercury's night side at the right time of year, they would see a faint orange glow from the sodium scattered by sunlight

One day on Mercury lasts 59 Earth days – an incredibly long time in comparison – while a year on Mercury lasts just 88 Earth days

NASA's MESSENGER mission stayed in orbit around Mercury from March 2011 to April 2015 before crashing into the surface of the planet

Astronomers believe there was active volcanism on Mercury at some point, as there are areas that appear to have been flooded with lava



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PLANET PROFILE

VENUS

EARTH'S SISTER PLANET IS A HARSH, DEADLY WORLD, MAKING IT AN INTERESTING ONE TO OBSERVE

Hell on Earth is a phrase used by many, but one planet matches this idea of a harsh and inhospitable environment – that accolade falls to Venus. The second planet from the Sun is similar in size and density to Earth, with it being only 638 kilometres (396 miles) smaller in diameter and 0.27 grams per cubic centimetre lower in density. These physical dimensions may paint a picture of a world similar to Earth, but that's far from the case. Venus underwent a different evolution, and its dense atmosphere has fashioned the hottest surface temperature in the entire Solar System at 465 degrees Celsius (869 degrees Fahrenheit), with atmospheric pressures that are over 90 times that of Earth's at sea level.

Venus' atmosphere is composed mainly of the greenhouse gas carbon dioxide, with small amounts of nitrogen and traces of other gases, most notably sulphur dioxide and argon. Comparing this atmosphere to Mars' – which is about 100 times thinner than Earth's – again highlights that these planetary evolutions took opposite approaches; one planet lost its atmospheric greenhouse gases, while the other formed a thick atmosphere, and as a result, traps heat in a runaway greenhouse effect.

In between these planets – both literally and scientifically – is Earth. It has moderate amounts of greenhouse gases that allow it to trap enough heat to maintain a habitable surface temperature that's perfect for the existence of life. Looking at the surface of Venus has revealed some extremely interesting characteristics that help astronomers and planetary scientists understand the planet's true interior. For instance, volcanoes have been observed on Venus, such as Idunn Mons in the planet's southern hemisphere, rising 2.5 kilometres (1.6 miles) above the surrounding plains. This volcanism is a sign that there is active mantle underneath the rocky surface. This would explain what is powering these volcanoes and also what is replenishing the sulphur dioxide in the atmosphere, creating the acidic clouds. It's also been theorised that Earthlike thunderstorms occur and sulphuric acid rain peppers Venus' surface, originating from the acidic clouds. Although volcanoes indicate that the planet's surface can be smoothed over by running lava, making it appear younger, there have still been many impact craters spotted on the surface.

Scientists have theoretically scratched the surface, revealing that the interior of Venus is likely composed of a partially liquid metallic core and a rocky mantle above that. This theory is based on the calculated mass and density of the planet, suggesting it's made up mainly of rocks and metals. This remains a theory for now due to observations being much harder because of the planet's thick atmosphere.

Venus hasn't had the same degree of surface visits and orbiter attention as Earth's neighbour on the other side, Mars, due to its lead-melting surface temperature and toxic acid clouds, but it has still been visited by several spacecraft. It has also been influential in providing a 'gravitational slingshot' to missions to more distant planets in the Solar System.

"VOLCANOES HAVE BEEN OBSERVED ON VENUS, SUCH AS IDUNN MONS IN THE PLANET'S SOUTHERN HEMISPHERE"

ATMOSPHERIC COMPOSITION

96.5%
CARBON DIOXIDE

3.5%
NITROGEN

150PPM*
SULPHUR DIOXIDE

70PPM*
ARGON

*PARTS PER MILLION

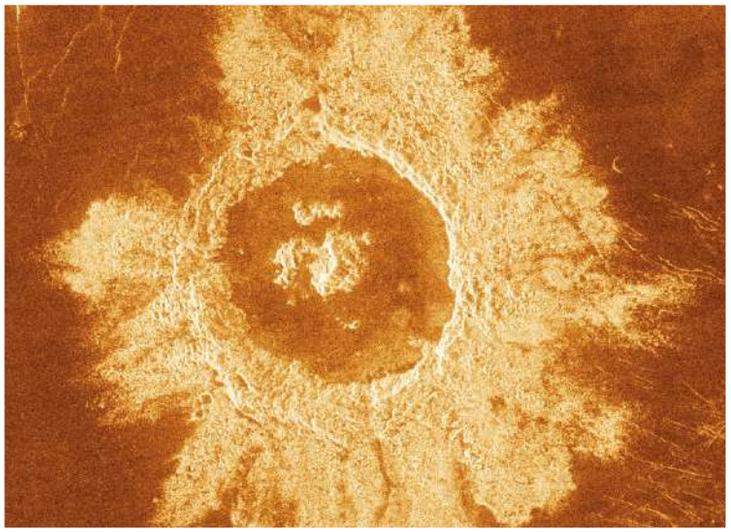
NEWS FROM VENUS

FORMING CRATERS ON DIFFERENT PLANETS

A recent study has been investigating how meteorites form impact craters – and in particular the features surrounding the craters called 'rays' – on extraterrestrial worlds that include Venus. These rays refer to the long, radial streaks that extend out from the centres of the craters out towards their rings. Scientists have been creating analogues to try and understand how these rays form by simply dropping a heavy metal ball onto a sand bed. However, the analogues weren't revealing the origin of the rays.

When Dr Tapan Sabuwala of the Okinawa Institute of Science and Technology Graduate University in Japan watched online videos of a ball-drop experiment by secondary-school students, he suddenly had a eureka moment. "These experiments are popular in science classes. I noticed that some of their experiments were producing crater rays," Sabuwala said. But what was the factor creating such features? It was the unevenness of the surface.

Generally, researchers will level out the sand bed during the experiments. However, the messiness of the surface appears to play a part in creating the rays. There have been many depressions and deformed mountain ranges observed on the surface of Venus. Unfortunately, the precise intricacies are still unknown. However, this does give a keen advantage when studying how impact craters are formed on different planets, of which Venus is included.



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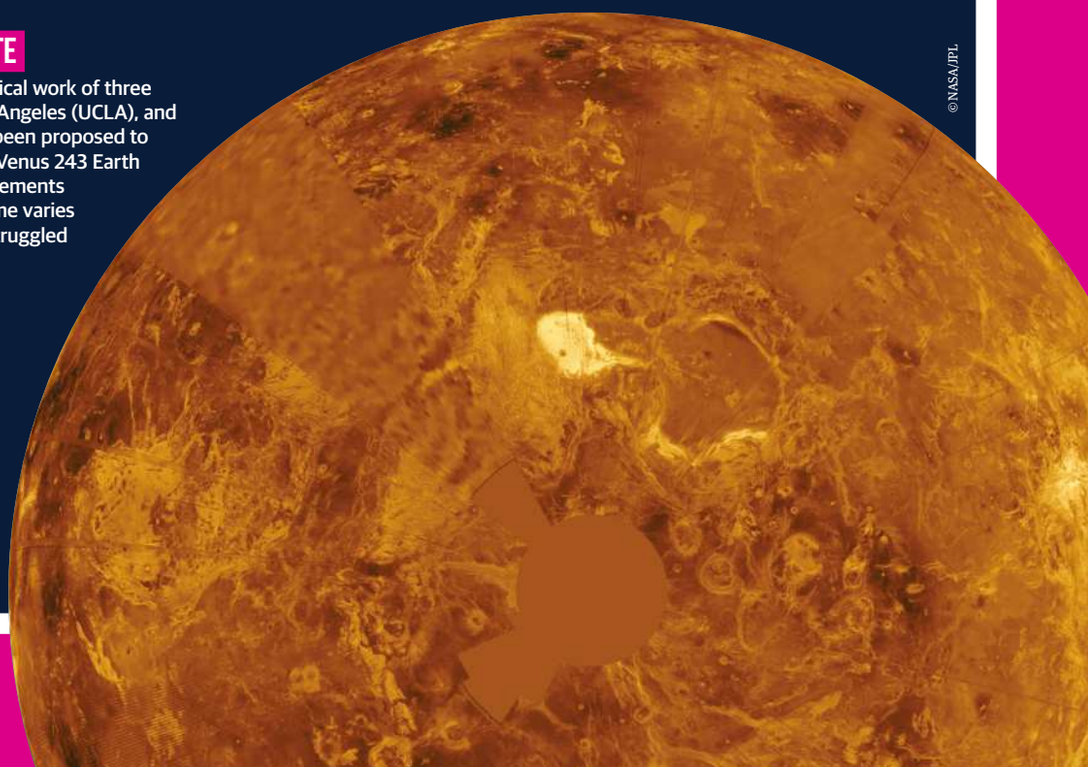
A PIECE OF VENUS ON EARTH

In a room of the Planetary Spectroscopy Laboratory (PSL) in Berlin, Germany, the German Space Agency has opened a new simulation facility that can bring the conditions of Venus to a laboratory. Because Venus' thick outer clouds make observations of the ground extremely hard, this facility allows scientists to analyse rock samples at temperatures of up to 1,000 degrees Celsius (1,830 degrees Fahrenheit). There have been many space-based observations of Venus from orbiters, such as the European Space Agency's (ESA) Venus Express and the Japan Aerospace Exploration Agency's (JAXA) Akatsuki, but this simulation can provide spectroscopic emission analysis of rock samples in a range of temperatures, as if actually on the surface of Venus. The results will complement the observations taken from the extraterrestrial missions. "PSL took up this challenge, building on nearly a decade of experience in high-temperature emission spectroscopy in the mid-infrared. After several years of development and extensive testing, PSL is now in routine operation for Venus-analogue emissivity measurements from 0.7 to 1.5 micrometres over the whole Venus surface temperature range," said Jörn Helbert of PSL, who led the development of the new facility.

EXPLAINING VENUS' WEIRD ROTATION RATE

By combining observational data with the theoretical work of three researchers from the University of California, Los Angeles (UCLA), and Sorbonne Université in France, a new theory has been proposed to explain the varied rotation rate of Venus. It takes Venus 243 Earth days to complete one spin, but with exact measurements made by Venus missions, it was found that this time varies by an average of seven minutes. Scientists have struggled to explain this deviation, but have also noticed that the planet's atmosphere orbits considerably quicker, completing one orbit in just four Earth days. Astronomers decided to take a look at the possibility of surface mountains carving a long-standing 10,000-kilometre (6,000-mile) wave in the thick atmosphere. On Earth these waves dissipate quickly due to rapid air currents, but Venus' atmosphere is much thicker. Simulations of this showed that the mountains can cause a two-minute variation in the planet's spin – not enough to account for the full seven minutes, but enough to suggest that other physical features can cause this variation.



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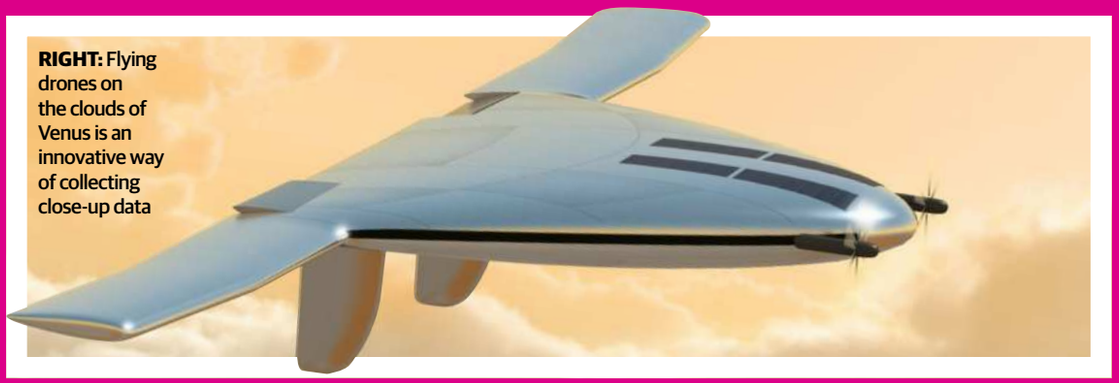
VISITING VENUS

We've sent spacecraft all over the Solar System, and Venus is no exception. The first came in 1962 with NASA's Mariner 2. This was the first successful spacecraft to visit another planet, but the Soviet Venera 7 became the first spacecraft to transmit data from the surface of Venus, for a total of 23 minutes. Venera 7 revealed the planet's scorching surface temperatures and crushing atmospheric pressures. Over a decade later, Venera 13 became the first lander to transmit colour images from the surface of Venus.

However, there was still so much more to learn about this mysterious, boiling planet. NASA sent the Pioneer probes and the Magellan spacecraft to Venus to reveal more of our sister planet's secrets. The ESA had its Venus Express orbiter, which was active between 2006 and 2015, and after a delayed orbital insertion, JAXA eventually placed its Akatsuki orbiter into orbit around Venus in 2015, where it currently remains.

Venus is visited by spacecraft relatively frequently as it's best used as a 'gravitational slingshot', providing a gravitational speed boost to spacecraft flying towards their next destination. However, scientists and engineers are coming up with new and creative ways of exploring other planets, with NASA awarding a contract to a drone-specialist company called Black Swift Technologies to develop a drone that can explore the upper atmosphere of Venus. The main reason behind this is that scientists now think that the most ideal conditions for life as we know it to survive on Venus reside in the cloud tops.



RIGHT: Flying drones on the clouds of Venus is an innovative way of collecting close-up data

EXPLORATION OF VENUS HIGHLIGHTS

- **Date:** 27 August 1962 **Agency:** NASA **Spacecraft:** Mariner 2
- **Date:** 12 June 1967 **Agency:** USSR **Spacecraft:** Venera 4
- **Date:** 14 June 1967 **Agency:** NASA **Spacecraft:** Mariner 5
- **Date:** 5 & 10 January 1969 **Agency:** USSR **Spacecraft:** Venera 5 & 6
- **Date:** 17 August 1970 **Agency:** USSR **Spacecraft:** Venera 7
- **Date:** 8 & 14 June 1975 **Agency:** USSR **Spacecraft:** Venera 9 & 10
- **Date:** 20 May 1978 **Agency:** NASA **Spacecraft:** Pioneer Venus 1
- **Date:** 8 August 1978 **Agency:** NASA **Spacecraft:** Pioneer Venus 2
- **Date:** 15 & 21 December 1984 **Agency:** USSR **Spacecraft:** Vega 1 & 2
- **Date:** 4 May 1989 **Agency:** NASA **Spacecraft:** Magellan
- **Date:** 18 October 1989 **Agency:** NASA **Spacecraft:** Galileo
- **Date:** 15 October 1997 **Agency:** NASA/ESA **Spacecraft:** Cassini-Huygens
- **Date:** 3 August 2004 **Agency:** NASA **Spacecraft:** MESSENGER
- **Date:** 9 November 2005 **Agency:** ESA **Spacecraft:** Venus Express
- **Date:** 20 May 2010 **Agency:** JAXA **Spacecraft:** Akatsuki

VENUS BY NUMBERS

TWO

The BepiColombo mission to Mercury underwent two flybys of Venus on 15 October 2020 and 10 August 2021

In the top layer of Venus' clouds, winds can reach up to 360 kilometres (224 miles) per hour – faster than hurricanes on Earth

650 BCE

Observations of Venus can be traced back to Mayan astronomers in 650 BCE, which led to a highly accurate calendar

243

A day on Venus lasts 243 Earth days, whereas a year on Venus only lasts 224.7 Earth days, oddly making a day longer than a year

11 KM

Maxwell Montes, the tallest mountain range on Venus, towers up to roughly 11 kilometres (seven miles) above the surface

Akatsuki was supposed to enter Venus orbit on 6 December 2010. It successfully entered orbit on 7 December 2015

KEY

Flyby · Orbiter · Lander

PLANET PROFILE

EARTH

THE ROCKY WORLD THAT WE CALL HOME IS FULL OF WONDERS

A rather pretty blue-and-white planet orbiting an otherwise obscure G-type main-sequence star, Earth is notable largely for being the only place in the universe to have evolved organic life. Other than this quirk of chemistry, the third planet from the Sun also has active plate tectonics, and it's one of the few planets whose moon fits perfectly over its Sun during an eclipse, leading to some fantastic sights. It is the densest planet in its Solar System, and the largest of the four rocky planets closest to its star. An atmosphere 100 kilometres (62 miles) thick coats the planet, offering it protection from UV light given out by the Sun thanks to its layer of ozone. Heating of the upper atmosphere means it's slowly losing its hydrogen and helium into space, but at a very slow rate.

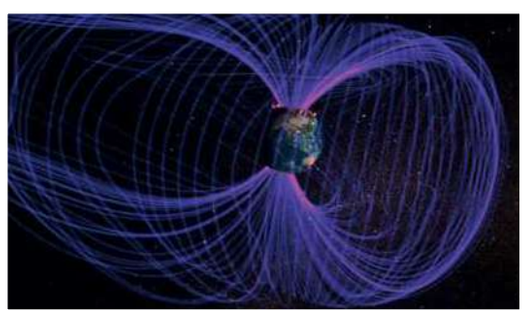
With its thick atmosphere and yellow sunlight, much of Earth's vegetation is green, though most of its inhabitants are not. Its position at around 150 million kilometres (93 million miles) from its star means liquid water is commonplace on its surface – both salty and non-salty forms, freezing at the poles – though a recent increase in atmospheric carbon dioxide levels is causing this ice to melt. Unlike its neighbour Mars, which is populated solely by robots, biological life flourishes both in Earth's oceans and on the third of the planet not covered with water.

An axial tilt of 23.5 degrees leads to seasons on the planet, which combine with both atmospheric and oceanic circulations to produce a variety of weather types, some of them extreme. A single, large natural satellite is tidally locked to the planet, and its gravitational pull affects the water level beneath it, causing tides. Along with the many artificial satellites created by its inhabitants, Earth also has a small number of quasi-satellites, mostly captured asteroids circulating around Lagrange points L4 and L5 in horseshoe orbits.

Earth is currently 20,000 years into an interglacial period, part of a cycle of ice ages that sees glaciers coat large parts of the planet over periods of up to 500,000 years. The current interglacial should end in around 25,000 years, though warming caused by increased atmospheric carbon dioxide levels could delay this by trapping heat within the atmosphere.

In a billion years' time, the energy received by Earth from its star will have increased by ten per cent, enough for the oceans to be lost thanks to a combination of subduction into the planet's mantle and photodissociation of the water molecules by increased levels of ultraviolet light. Without surface water, the planet's plate tectonics will come to a halt. Earth will become similar to its near-twin Venus, its neighbour on the sunward side, with a runaway greenhouse effect eventually raising the surface temperature to 1,330 degrees Celsius (2,426 degrees Fahrenheit).

In another 5 billion years, the Sun will run out of hydrogen to burn in its core and will begin the process of swelling into a red giant. As it expands, Earth, along with Venus and the small rocky planet Mercury, will be engulfed by its chromosphere. Tidal forces will break up the Moon, briefly turning it into a ring system before the surface and mantle are stripped from the Earth, leaving only its core. The final legacy of Earth will be an increase in the Sun's metal content of 0.01 per cent.



LEFT: Earth is surrounded by a magnetic bubble called its magnetosphere

"WITH ITS THICK ATMOSPHERE AND YELLOW SUNLIGHT,MUCH OF EARTH'S VEGETATION IS GREEN"

COMPOSITION

32.1% IRON

30.1% OXYGEN

15.1% SILICON

13.9% MAGNESIUM

2.9% SULPHUR

1.8% NICKEL

1.5% CALCIUM

1.4% ALUMINIUM

1.2% TRACES OF OTHER ELEMENTS

NEWS FROM EARTH

EXTINCTION EVENT

A study published in the journal *Biological Conservation* suggests that 84 per cent of animals and plants in mountain regions risk being wiped out if the planet's temperature rises by more than an average of three degrees Celsius (5.4 degrees Fahrenheit), with this rising to 100 per cent on islands.

Geographically unique species such as Madagascar's lemurs and the snow leopards of the Himalayas are 2.7 times more likely to go extinct than species that are more widespread. More than 60 per cent of unique tropical species are likely to go extinct thanks to the action of climate change alone, and places such as the Caribbean islands and Sri Lanka could lose most of their endemic plants by 2050. Up to 92 per cent of species on land and 95 per cent of those in the sea could face negative consequences.

The researchers – from Brazil, Norway and South Africa, among others – concluded that if the world can keep global average temperature rises within the terms of the Paris Climate Agreement, then the risk to vulnerable species drops by a factor of ten. With a 1.5 degrees Celsius (2.7 degrees Fahrenheit) rise, only two per cent of land and marine species face extinction.

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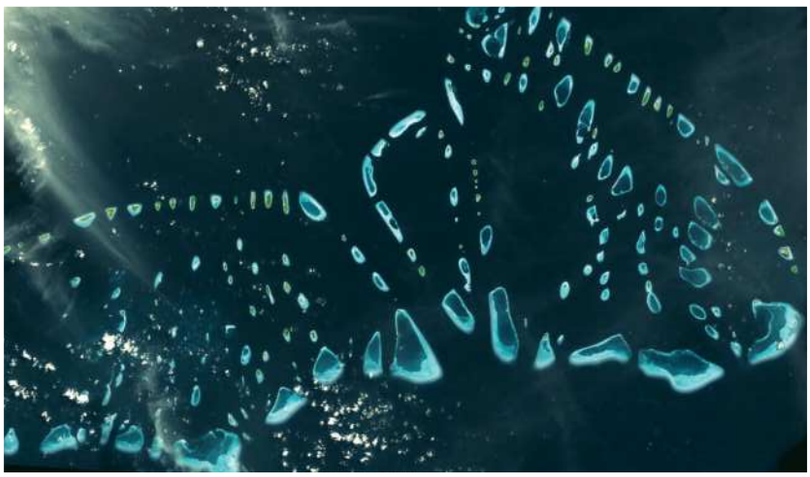


© NASA

ARTIFICIAL ISLAND

Not content with all the islands already available to it, the dominant mammal species on Earth has been busy making more. A new artificial island near Malé, the capital of the Republic of Maldives, an archipelago in the Indian Ocean, will act as a refuge for people stranded by rising sea levels. With more than 80 per cent of its 1,190 islands just one metre (3.2 feet) above the water, the Maldives has the lowest terrain of any country in the world, which makes it particularly susceptible to sea-level rise. Construction of the new island, known as Hulhumalé, began in 1997, and it has grown to over four square kilometres (1.5 square miles) in area. It sits two metres (6.5 feet) above sea level, constructed from sand pumped on top of submerged coral, and is now the fourth-largest island in the archipelago.

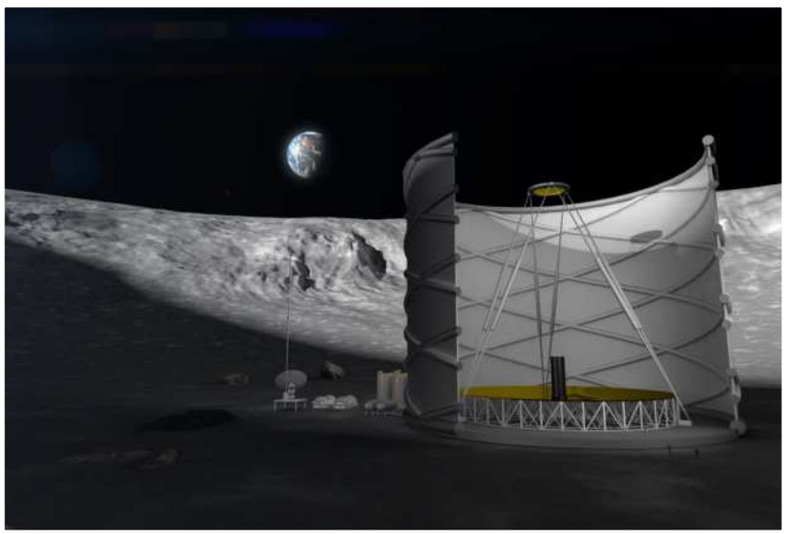
With sea levels predicted to rise by up to half a metre by 2100 even if the Paris Climate Agreement targets are hit, land reclamation projects like this may become more common as populations are driven from low-lying areas.

MOON TELESCOPE

An early-stage proposal has received funding from NASA to build a radio telescope in a crater on the far side of the Moon. Similar in concept to the Arecibo Observatory, the Lunar Crater Radio Telescope would take advantage of the Moon's many meteor craters to support its structure.

Because of the way Earth and the Moon are tidally locked, one side of the Moon always faces away from us. The advantage of building such a device on the Moon, particularly on its far side, is the shielding effect it gives against Earth-generated noise and even the radio waves emitted by the Sun. It would also be able to observe the universe at frequencies that are blocked by Earth's atmosphere, such as those below 30MHz. Observations in these wavebands have never been made by humans.

The proposal is to deploy two wall-climbing robots in a crater three to five kilometres (1.8 to 3.1 miles) in diameter. The robots would then weave a dish one kilometre (0.62 miles) across using a wire mesh. A receiver would then be suspended above this dish on two crossed cables, each end held by a robot that would be able to move, adjusting the position of the receiver for the best results.



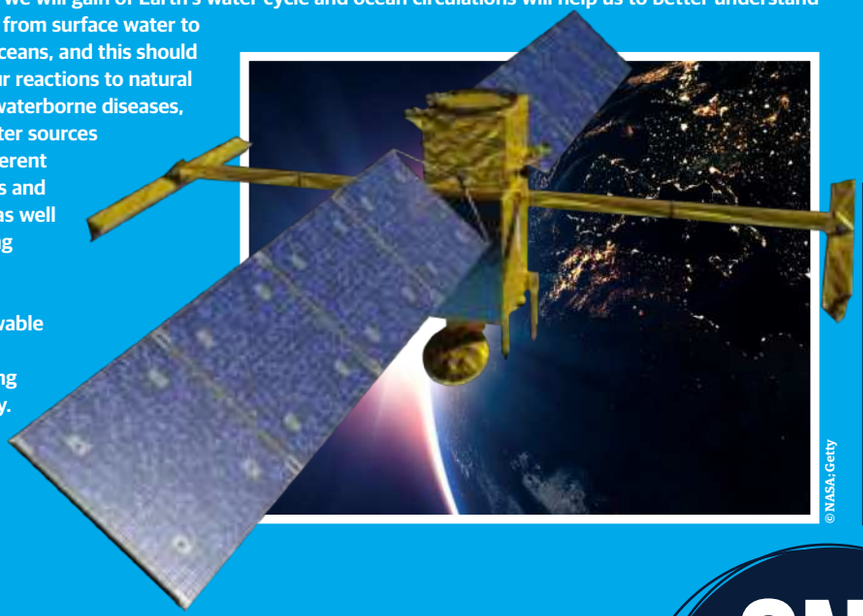
© Adrian Mann

SURFACE WATER AND OCEAN TOPOGRAPHY MISSION

Due to launch in November 2022, SWOT – a joint development between NASA and French space agency CNES, with help from Canada and the UK – is designed to accurately measure the height of Earth's surface water. The SWOT mission aims to measure how bodies of water change over time. It will use a radar altimeter to measure the height of oceans, rivers and lakes across 90 per cent of the globe at least twice every 21 days at an average precision better than 1.5 centimetres (0.6 inches).

This data will lead to better weather and climate forecasting, providing more accurate information about sea and river levels that can be plugged into the supercomputer prediction models used by meteorological agencies. It will also be able to measure the 3D shape of floodwater, track flood levels and improve our ability to predict future floods.

The largest effect SWOT may have on Earth's population is the data it will provide about freshwater management. This will help urban planners to manage the distribution of water for agricultural, industrial and urban needs by providing information about reservoirs and major rivers. The enhanced knowledge we will gain of Earth's water cycle and ocean circulations will help us to better understand everything from surface water to the deep oceans, and this should improve our reactions to natural disasters, waterborne diseases, sharing water sources among different populations and countries, as well as managing electricity production from renewable means and safeguarding biodiversity.



© NASA: Getty

LEFT: Artist's model of the SWOT spacecraft

BELOW RIGHT: The structure of the Earth from the surface crust down to the solid inner core

PLANET EARTH BY NUMBERS

ONE
NATURAL SATELLITE

ONE
ATMOSPHERE
Mean surface pressure

43KM
The difference in the Earth's diameter at the equator than if measured pole-to-pole

14°C
Average surface temperature

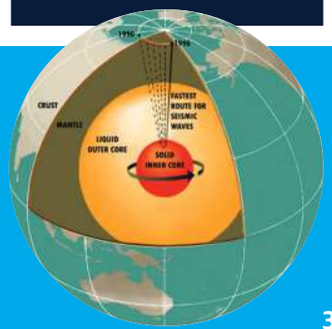
5,430°C
Temperature at inner core

1G
Average surface gravity

1AU
Average distance to Sun

THE EVOLUTION OF PLANET EARTH

- **Date:** 4.54 billion years ago **Activity:** Earth formed from a protoplanetary disc around a young star.
- **Date:** 4.5 billion years ago **Activity:** Dense elements sank to the centre, forming Earth's core, while the outside layer cooled and solidified.
- **Date:** 4.48 billion years ago **Activity:** A massive impact with another body sent a portion of Earth's crust into orbit, forming the Moon.
- **Date:** 4.4 billion years ago **Activity:** Volcanism released water vapour into Earth's atmosphere, raining down to begin the formation of the planet's oceans.
- **Date:** 3.5 billion years ago **Activity:** Earth's magnetic field was established, with a magnetosphere about half the modern radius.
- **Date:** 750 million years ago **Activity:** The earliest known supercontinent, Rodinia, began to break apart.
- **Date:** 180 million years ago **Activity:** The most recent supercontinent, Pangaea, broke apart.
- **Date:** 65 million years ago **Activity:** Formation of the Himalayas began as the Indian subcontinent drifted into Asia.
- **Date:** 6 million years ago **Activity:** A small African ape began a family tree that led to a dominant species.



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THE CRASH THAT MADE

OUR MOON

UNDERSTANDING HOW OUR LUNAR COMPANION WAS FORMED MIGHT JUST EXPLAIN HOW WE CAME TO BE HERE

It's the brightest thing in our night sky. Over the course of history it has been revered as a god, trampled across by 12 extraordinary explorers and immortalised in poetry. The Moon is our steadfast companion, our only natural satellite as we endlessly orbit our nearest star: the Sun. Yet for an object that has received such scrutiny, arguments rage about where exactly the Moon came from. A suitable explanation needs to take into account what is perhaps the Moon's greatest oddity: its size. It is the fifth-largest moon in the Solar System, trumping most of the satellites of our much bigger planetary neighbours. If you compare the size of moons to the size of their host planet, ours comes out at the very top. Many of the smaller moons of the Solar System are thought to be captured worlds – bodies that wandered too close to a planet before getting snared in its gravitational pull. Given the size of our Moon, it's hard to imagine that's how it ended up circling Earth.

As far back as 1878, George Darwin – the astronomer son of famous naturalist Charles Darwin – instead proposed that Earth and the Moon were once one body and that the latter formed from material thrown off the spinning Earth. This, he said, would explain why the Moon was moving a little further away from us each year. Supporters of this idea even pointed to the lack of land in the Pacific Ocean – which

© NASA

stretches across half of our planet – as the birthplace of the Moon. However, scientists later realised that any force capable of dislodging such a large amount of Earthly material would most likely have destroyed the rest of our planet at the same time.

Attention turned instead to the idea of a giant impact – one that occurred 4.5 billion years ago when a young Earth was still forming. It must have been this early because the rocks brought back from the Moon are that old. Astronomers have long believed that the Solar System had a tempestuous infancy, throwing around huge lumps of rock and metal before eventually calming down. What if one of these objects – perhaps one the size of Mars – hit the young Earth, with the Moon forming out of the hot, spinning debris?

On the face of it this idea makes a lot of sense. We know from the dark patches on the lunar surface that parts of the Moon were once molten. The Moon also has a pretty small iron core – much smaller than Earth's – and it is less dense than Earth. This also fits, because during an impact the lightest material would have been thrown the furthest, leaving the heavier stuff here on Earth. Astronomers have a name for this proposed Mars-sized impactor: Theia, named after the Titan who gave birth to the Moon goddess Selene in Greek mythology. Computer modelling has been used to try and figure out what this impact must have been like in order for it to form the modern Moon. Traditionally, the best fit seems to come from a glancing blow – Theia clipping Earth at an angle of about 45 degrees – and at a relatively slow speed. The debris from the impact, mostly formed from the leftover remnants of Theia, would have formed a ring around Earth, which then coalesced into the Moon. But recent analysis of Moon rocks returned to Earth during the Apollo missions appears to throw a spanner in the works.

It is all to do with isotopes. What sets different chemical elements apart is the number of protons present in the nucleus of their atoms. Oxygen,

"IF THE MOON WAS MOSTLY FORMED FROM A SMASHED-APART THEIA DURING A GLANCING BLOW WITH EARTH, IT SHOULD HAVE ITS OWN UNIQUE OXYGEN ISOTOPE SIGNATURE. YET INSTEAD IT MATCHES EARTH'S EXACTLY"

ABOVE LEFT: Astronaut Harrison Schmitt is seen covered in lunar dirt while collecting samples during the Apollo 17 mission

HOW THE MOON WASN'T MADE

It was flung off a rapidly spinning Earth

What is it?

An idea which was popular for decades was that the material which makes up the Moon was once part of Earth. It suggested the Moon separated from Earth while it was semi-molten and spinning rapidly, and many saw the Pacific Ocean as a void created by the departing material. Darwin backed up the idea with solid and accurate calculations.

Why it's wrong

By the 1930s calculations showed that Earth would have had to spin at an inconceivable rate to throw off enough material to form the Moon.

It was made elsewhere and captured by Earth

What is it?

Many of the moons in our Solar System are thought to be captured objects – Phobos and Deimos around Mars are good examples. It isn't inconceivable that Earth could have captured the Moon, as this would explain why the Moon and Earth appear to have different densities.

Why it's wrong

For Earth to capture a large Moon, both objects would have to travel slowly – a collision was more probable. It's also unlikely that Earth's gravity would've been able to hold the Moon for so long.

It was formed at the same time as Earth

What is it?

The co-accretion idea is that Earth and the Moon formed together in the early Solar System from the debris around the newborn Sun. Support came from observations of double stars. If two distinct stars could form out of a nebula, then it seemed at least possible that two worlds might coalesce side by side in orbit around a single star.

Why it's wrong

While the oxygen isotopes may be the same, the densities of Earth and the Moon and the amounts of iron on each are different.

© Tobias Roetsch

HOW THE MOON WAS MADE

1 Theia approaches Earth

A Mars-sized object is on an unalterable collision course with the early Earth.

2 Earth gets hit

The impactor hits Earth in a head-on collision, vaporising both Theia and Earth's mantle.

3 Material is thrown out

The vaporised material from both bodies mixes and is thrown outwards by the huge impact.

4 Debris gathers

Smaller objects begin to condense out of the vapour while continuing to orbit around Earth.

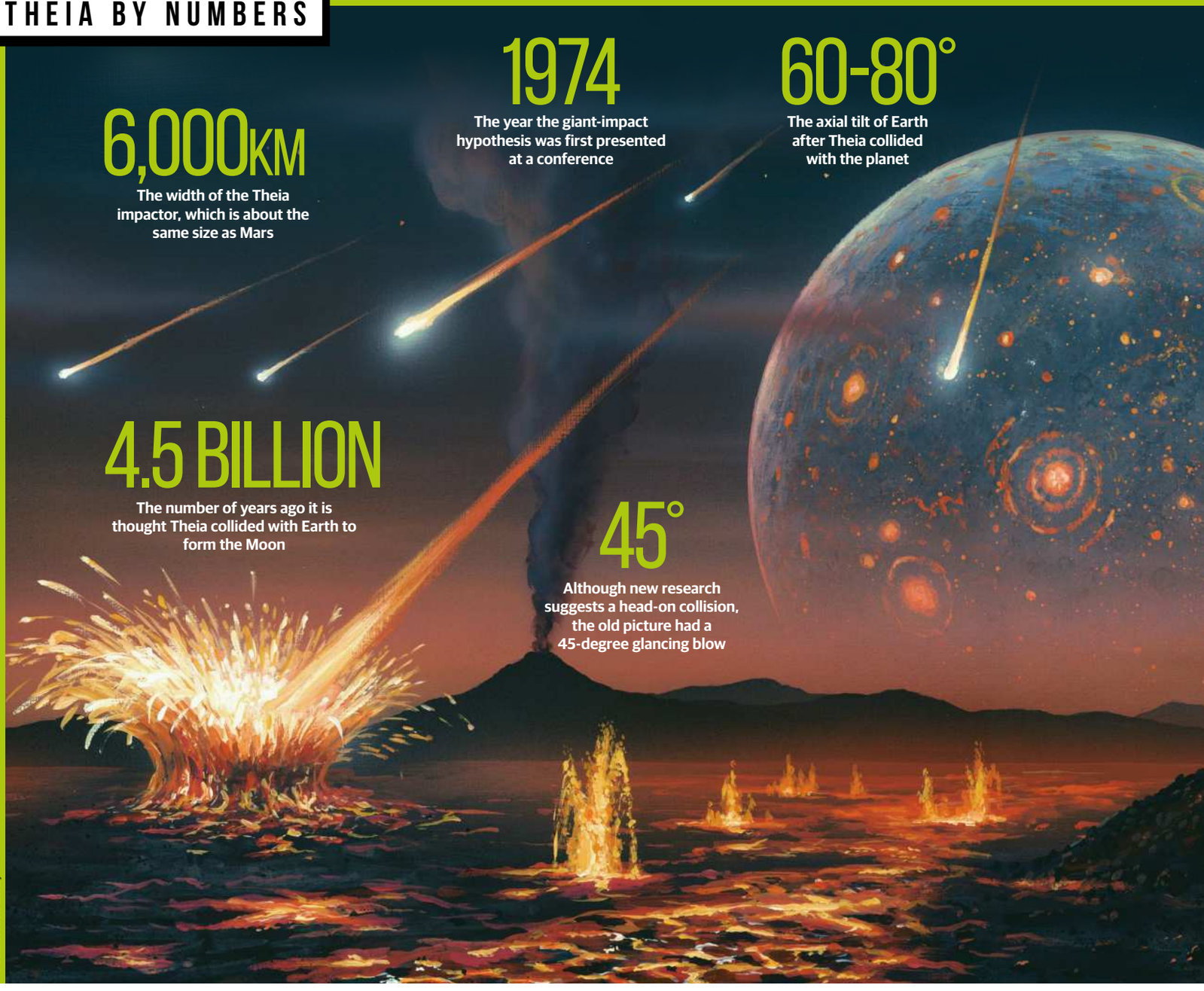
5 The Moon takes shape

Many of the smaller objects stick together to form a proto-Moon in orbit around Earth.

6 Our companion is formed

Eventually all the pieces come together to form the basis of the Moon that we see today.

THEIA BY NUMBERS



for example, always has eight. Add another proton and you get an entirely different element – fluorine in this case. But several versions of the same element can exist, each with the same number of protons but a differing number of neutrons. Scientists call these different flavours of the same element 'isotopes'. Oxygen, for example, has three stable isotopes, with eight, nine or ten neutrons.

When it comes to planetary geology, the relative amounts of each of these isotopes present on a celestial object are a key measurement, a bit like a fingerprint. "Each body in the Solar System has a unique oxygen isotope signature," says Dr Kun Wang, assistant professor of Earth and planetary sciences at Washington University in St Louis. And therein lies the problem. Analysis of the Apollo samples shows that Moon rocks have exactly the same oxygen isotope signature as Earth. If the Moon was mostly formed from a smashed-apart Theia during a glancing blow with Earth, it should have its own unique oxygen isotope signature. Yet instead it matches Earth's signature exactly.

Scientists first discovered this as far back as 2001, but many believed that this apparent similarity was just an artefact of the precision of the experiments – that one day more accurate analysis would show there to be a tiny difference after all. However, the latest research published found that even with much more precise measurements, the oxygen isotope signature is still identical. Therefore the Moon did not form from Theia alone.

Wang believes this points to a much more violent collision, one which melted the outer layers of both Earth and Theia. This material then mixed together to form a vapour – a cloud of material – stretching from our planet out to 500 Earth radii. The Moon then condensed from this cloud, explaining why both bodies now have the same oxygen isotopes. "Once they mix together it doesn't matter what the oxygen isotopes of the two bodies were before," says Wang. But if the notion of a more catastrophic impact is to be accepted, it needs more than one strand of supporting evidence, so that is exactly what Wang set out to find.

He analysed seven different Moon rock samples from multiple Apollo missions, along with samples of Earth rocks, measuring the different abundances of isotopes of potassium using a technique ten-times more accurate than previously possible. In October 2016, along

2000

The year that the name Theia was proposed by English geochemist Alex Halliday

with his colleague Stein Jacobsen from Harvard University, he published his results. He found that the Moon rocks had a greater abundance of one particular potassium isotope at the level of 0.4 parts per 1,000 more than Earth. "Potassium is a lot more volatile than oxygen, meaning it is more likely to vaporise and be mobile after the collision," says Helen Williams, an Earth scientist at the University of Cambridge. The potassium was therefore much more likely to end up far away from Earth and become incorporated as part of the Moon. But for potassium to be vaporised in the first place, the collision must have vaporised both Theia and much of Earth's surface. To Wang, that has all the hallmarks of a head-on collision rather than a glancing blow.

But even if he is correct there are still some outstanding Moon mysteries in need of explanation – none more so than the unusual tilt of the Moon's orbit around Earth. The Moon would have initially formed in an orbit matching the orientation of Earth's equator. As it moved further from our planet, the gravitational pull of the Sun would have forced it into line with the orbits of the other planets – a plane known as the 'ecliptic'. Yet today's Moon orbits at an angle of five degrees to the ecliptic. "That might not sound like much, but all the other big moons of the Solar System are inclined at less than

LEFT: Mars-sized Theia approaches the still-molten Earth before the collision

BELOW: Wearing special germ-free clothing, Dr Robert Gilruth (right) inspects lunar samples from the Apollo 17 mission

"THE MOON ROCKS HAD A GREATER ABUNDANCE OF ONE PARTICULAR POTASSIUM ISOTOPE AT THE LEVEL OF 0.4 PARTS PER 1,000 MORE THAN EARTH"

© NASA

MOON ROCK ANALYSIS

The age of the Moon

Analysis of lunar rocks suggests the Moon is almost as old as Earth, meaning the collision happened within Earth's first 100 million years.

Matching oxygen isotopes

The relative abundances of the three stable isotopes of oxygen are the same on Earth and the Moon, suggesting a common origin.

No sign of water

The Moon rocks show no signs of past interaction with water. All the geology can be explained as rocks being under pressure.

Differing potassium isotopes

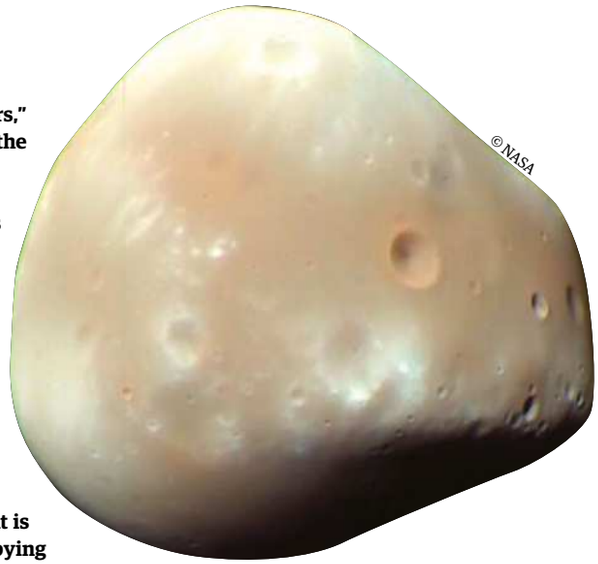
There is slightly more of one particular potassium isotope on the Moon, pointing to it being vaporised during a head-on collision.

Source: Wikipedia Commons © Bryce Edwards

a degree to their planets – so the Moon really stands out," says Douglas Hamilton, professor of astronomy at the University of Maryland. A team led by Hamilton has recently attempted to explain this strange anomaly. They ran many computer simulations of the giant impact, with slightly different parameters each time. The one that gave the closest match to the Moon's current orbit suggests Theia's impact was a lot more calamitous for our planet than previous models have suggested.

The wallop from Theia would have sent Earth spinning much faster. More than twice as fast, in fact, as other previous models have suggested. What's more, Earth would have been knocked over almost on its side, with its axis tilted somewhere between 60 and 80 degrees to the ecliptic – today it is only tilted by 23.4 degrees.

This high inclination affected the Moon as it retreated from Earth, forcing it into an orbit tilted at an angle of around 30 degrees to the ecliptic. "It then settled down to five degrees over the last 4.5 billion years," says Hamilton. At the same time Earth's axis started to straighten up to its present position. It just goes to show that our ideas about the formation of the Moon are still very much in flux. Quite how we came to have such a large Moon on an inclined orbit is a puzzle still occupying teams of astronomers around the world. But it seems we are getting closer.



LEFT: Unlike Mars' moon Deimos, our Moon wasn't captured as it passed by our planet

BELOW: We are still not certain on how the Moon ended up in orbit around Earth

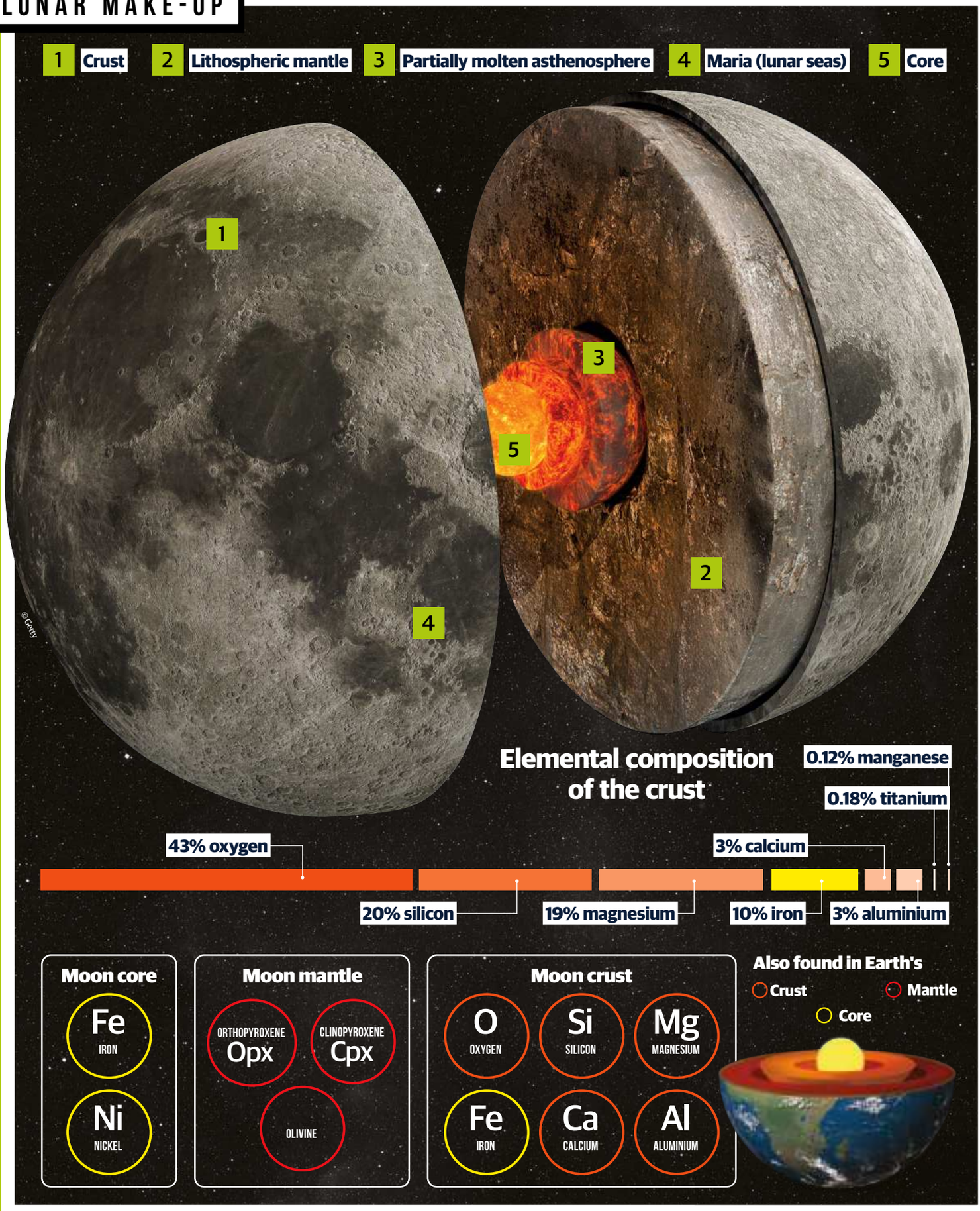
And that's very important, because discovering the Moon's history is a key step in understanding how likely such events are in the wider universe.

This in turn might help us answer a much bigger question: whether we are alone in the universe. That's because many scientists have speculated that the churning of the oceans by a Moon that was much closer to Earth than it is today could have played a key role in the early development of life on Earth. Its gravitational pull also stabilises Earth's axis, keeping our seasons steady and reliable every year. This flurry of recent lunar research has put us one step closer to understanding how our Moon came to be, and may even one day help us understand our place in the universe.

"EARTH WOULD HAVE BEEN KNOCKED OVER ALMOST ON ITS SIDE, WITH ITS AXIS TILTED SOMEWHERE BETWEEN 60 AND 80 DEGREES TO THE ECLIPTIC"

© NASA

LUNAR MAKE-UP



PLANET PROFILE
MARS

THE RED PLANET HAS A HOST OF NEW ROBOTS INVESTIGATING IT

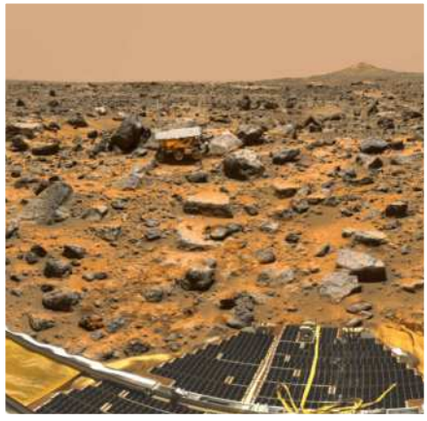
Across the gulf of space, no other planet has fired humanity's imagination so much as the Red Planet, and it has frequently been associated with violence, war and death. To the ancient Sumerians, it was Nergal, a god of war and plague who presided over the netherworld. In Mesopotamia, it was the 'star of judgement of the fate of the dead'. The Chinese associated it with the element fire, while for the people of the Tiwi Islands off the coast of Australia the planet was one of the four wives of the Moon Man, who followed the path of the Sun Woman through the sky – the other wives were Mercury, Jupiter and Venus. The planet was a familiar sight to the astronomers of ancient Egypt, Babylonia, Rome – where Mars was the god of war – and Greece, where Aristotle noticed that the planet vanished behind the Moon during an occultation, proving it was farther away.

Following the invention of the telescope in the 17th century, Mars could be observed in greater detail, and Christiaan Huygens was able to observe Syrtis Major – which he thought was a plain, but we now know to be a volcano – the first surface feature seen on another planet, in 1659. He was also able to measure Mars' day length as 24 hours and 30 minutes – only seven minutes short of the true value.

It would be another 312 years before a human-made spacecraft would touch down on Martian soil, with the Soviet Union's Mars 3 lasting 110 seconds on the surface and managing to transmit only part of a single image that showed no detail. There would be several more failures until NASA's Viking 1 touched down in 1976 and operated for over six years.

Exploration of the planet has continued, and right now there are three operational rovers on its surface. Curiosity and Perseverance are from the US, while Zhurong hails from China. These missions are the lucky ones. There have been a spate of failed missions from the USSR, US, UK and Japan – from rocket failures and solar panels failing to open to a mix-up between the units of measurement used in America and the metric system used by most of the rest of the world, which caused NASA's Mars Climate Orbiter to either burn up or skip off the Martian atmosphere and into deep space in 1999.

Human missions to Mars have been a dream since the earliest days of space exploration. In 2004 the Vision for Space Exploration announced by US president George W. Bush called for a crewed mission to the Moon in 2020 as a stepping stone to Mars. In 2007 NASA administrator Michael D. Griffin said the agency aimed to put a person on Mars by 2037. The Journey to Mars plan, formulated by NASA in 2015, uses the ISS and an asteroid captured in 2020 to test deep-space habitation facilities. That phase is behind schedule, but the ISS phase is underway and set to last until 2024. Humans on Mars in the 2030s is still NASA's goal.



LEFT: Mars Pathfinder explores the rocky surface of the Red Planet

ABOVE: Mars' north pole, taken by the Mars Global Surveyor

BELOW: Mars Global Surveyor image of ice at the south pole

ATMOSPHERIC COMPOSITION

95% CARBON DIOXIDE

2.6% MOLECULAR NITROGEN

1.9% ARGON

0.16% MOLECULAR OXYGEN

0.06% CARBON MONOXIDE

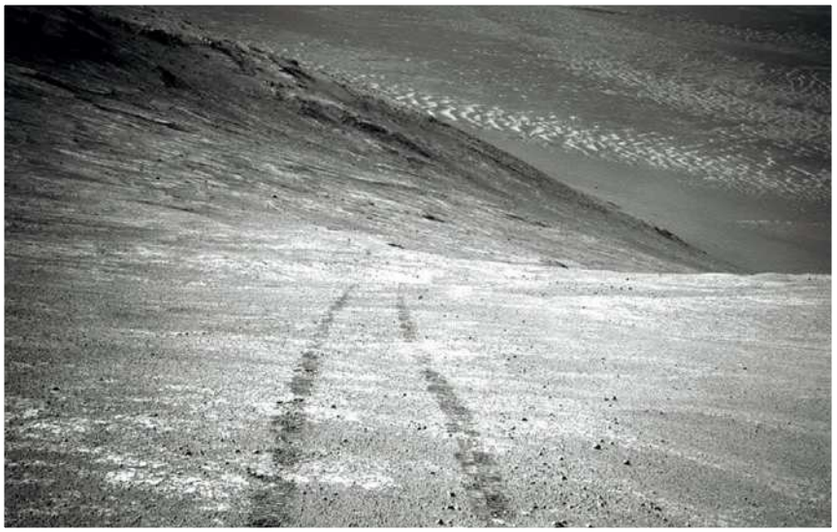
0.03% WATER VAPOUR

NEWS FROM MARS

RENEWABLE ENERGY ON MARS

Renewable power is a little bit tricky on Mars, which is farther from the Sun, has dust storms and has no tides. What it does have, however, is wind, and so scientists from Delft University of Technology have come up with an excellent idea of designing robots to fly huge power-generating kites in the Martian atmosphere. "Despite the low density of the Martian atmosphere, wind speeds are high enough to make wind energy competitive with nuclear power in terms of power produced per unit mass," the scientists wrote in a research paper. One kite could generate 127 megawatt-hours of energy per year, the scientists say, enough to power five households in the US.

The assembly, which will also have solar panels – though Mars gets only 43 per cent of the sunlight we enjoy on Earth – will catch the wind and be reeled out, performing a series of tacking manoeuvres to maximise its speed and pulling force. This is all controlled by a robot that steers the wing-like kite, changing its angle of attack. Once the cable is pulled out, the kite can be dropped to minimise the pull as it's reeled back in, ready to fly again.



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OXYGEN ON MARS

The atmosphere on Mars is thin and not conducive to effective human breathing. It's a hostile environment, and any astronauts who explore there will need to take their own oxygen. If humans are to build an outpost on the planet, however, they need a way of generating their own oxygen, which is also a critical component of rocket fuel. NASA estimates getting four astronauts back from Mars would take about 25 tonnes of the gas.

Enter the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE), carried aboard NASA's Perseverance rover. This uses 300 watts of power to heat carbon dioxide from the Martian atmosphere, where it strips the oxygen atoms away from the carbon and sends the resulting carbon monoxide back outside. During its first test in April, it created just over five grams of oxygen in an hour, which is about ten minutes of breathing for an astronaut. MOXIE is just a demonstrator, but larger, more powerful versions of it could one day produce enough oxygen for a colony.

INGENUITY WOBBLES, BUT FLIES ON

The small robotic helicopter carried by NASA's Perseverance rover has made 29 flights across the Martian surface since its landing on 18 February 2021. It hasn't been an entirely smooth process, however.

On the helicopter's sixth flight on 23 May 2021, it was asked to climb to ten metres (33 feet) above the surface before flying to the west to take images of a region of interest there. During flight, a glitch was noticed in the stream of images coming from the craft's camera. Ingenuity began adjusting its velocity and tilting back and forth in an oscillating pattern, and this behaviour persisted for the rest of the flight. It encountered roll and pitch excursions of more than 20 degrees and spikes in power consumption. Despite this, it was able to land within five metres (16.5 feet) of its intended location.

In May 2022, Ingenuity failed to communicate with Perseverance due to a low battery charge, however communication was restored a day later. On 6 June, the craft's inclination sensor stopped working but a workaround was established meaning that the plucky helicopter continues to explore the Martian surface.

© NASA

NUCLEAR ROCKETS

All this talk of oxygen and energy is all well and good, but before you can start deploying these technologies on Mars you've got to get there. NASA has explored the Solar System using a range of chemical rockets and gas-fuelled manoeuvring systems, but is investigating two methods of nuclear propulsion to speed humanity to the Red Planet.

© NASA

The first is nuclear electric propulsion, otherwise known as the ion drive, which supplies low thrust over a long interval to gradually build high acceleration. The other is nuclear thermal propulsion, which provides high thrust and twice the propellant efficiency of chemical rockets. NASA is looking into preliminary reactor design concepts for such a rocket, which heats a fluid, usually liquid hydrogen, in a nuclear reactor. Once it reaches a high enough temperature, the fluid expands through a rocket nozzle to create thrust.

Nuclear thermal propulsion has been on NASA's radar for more than 60 years. Research on the subject once concentrated on fission reactors, but these came with a number of problems, notably that no one wanted a flying fission reactor with even a chance of exploding over their heads. Recent research has moved to nuclear fusion power, and such a rocket could be constructed in orbit as an additional safety measure. Nuclear propulsion could enable missions to Mars at times when the planet is not favourably positioned relative to Earth, and could cut the round trip time of a crewed mission to just two years.

ABOVE: Illustration of a Mars transit habitat and nuclear propulsion system that could one day take astronauts to Mars

EVOLUTION OF THE RED PLANET

- **Date:** 4.57 billion years ago
  Activity: Mars was part of the same protoplanetary disc as the other planets, swirling around the nascent Sun.
- **Date:** 4 billion years ago
  Activity: The Late Heavy Bombardment scarred Mars' surface – these craters can still be seen today.
- **Date:** 4 billion years ago
  Activity: Mars was hit by a body the size of Pluto, creating the smooth Borealis Basin that covers 40 per cent of Mars.
- **Date:** 3.8 billion years ago
  Activity: Substantial amounts of liquid water on the surface began to dry up due to the loss of the planet's magnetic field and its atmosphere.
- **Date:** 3.3 billion years ago
  Activity: Olympus Mons, a huge volcano, formed as part of a period of enormous geological activity.
- **Date:** 237 years ago
  Activity: Astronomer William Herschel declared Mars would offer "a situation in many respects similar to ours".
- **Date:** 144 years ago
  Activity: Asaph Hall discovered Phobos and Deimos, the Martian moons.
- **Date:** 50 years ago
  Activity: Humans started dropping craft and robots onto the surface, but many of these fail.

MARS BY NUMBERS

15%
Mars is 15 per cent of Earth's volume

8 METERS
There is eight metres of permanent frozen CO_2 at the south pole

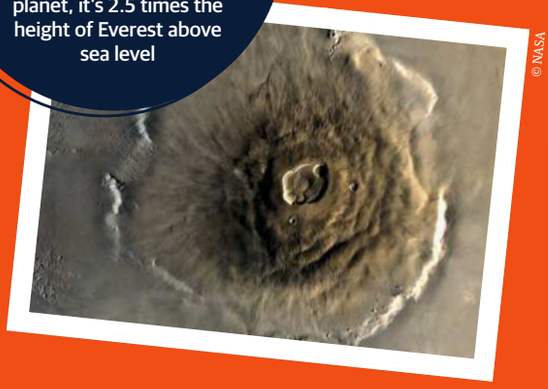
38%
Its gravity is 38 per cent of Earth's

70%
The polar caps are 70 per cent water ice

OLYMPUS MONS
The tallest mountain of any planet, it's 2.5 times the height of Everest above sea level

11%
Mars has 11 per cent of Earth's mass

7.7
Its soil pH is 7.7, which is slightly alkaline



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LEFT: Olympus Mons is a dormant shield volcano, the biggest in the Solar System

PLANET PROFILE

JUPITER

THE LARGEST PLANET HAS A LOT TO TELL US

Fifth in the eight-planet line-up of our Solar System, Jupiter also happens to be the largest, and by quite some distance. The mass of this gigantic ball of gas is two-and-a-half times that of all the other planets put together, and you could fit 11.2 Earths within its radius. While there's likely a rocky core somewhere under the enormous gaseous atmosphere, scientists can't be sure whether it's solid or not, but gravitational measurements suggest it could make up as much as 15 per cent of Jupiter's mass.

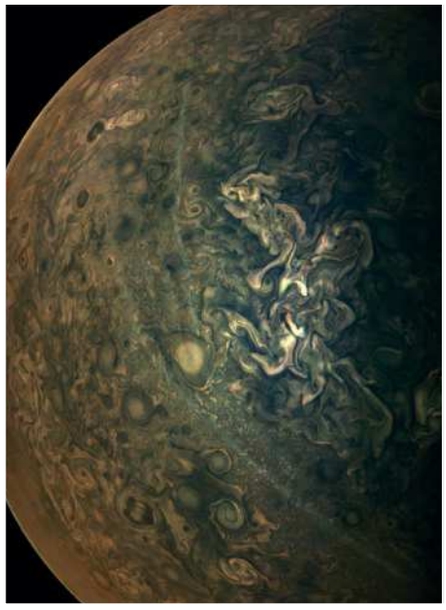
What is known is that Jupiter is contracting, and this generates more heat than the planet receives from the Sun, warming the huge number of moons that orbit around it. It also has a faint ring system, too thin to be seen from Earth with any but the largest telescopes and was first spotted by the Voyager 1 probe in 1979.

Jupiter plays a major role in many theories of the formation of our Solar System. In one, known as the grand tack hypothesis, Jupiter formed at 3.5 AU – 1 AU is the Earth-Sun distance – before plunging inward towards the Sun until it reached 1.5 AU, then reversing course and moving out again, stopping at its current distance of 5.2 AU. It crossed the asteroid belt twice, scattering rocks in all directions and contributing to the low mass of the belt today. It may also have caused rocky planets orbiting closer to the Sun to crash into the star's surface. This answers questions such as why Mars is so small – Jupiter's presence limited the material available for its formation – and why there are no large planets orbiting close to the Sun, as we see in other solar systems.

Jupiter has also had a long-lasting effect on the rest of the Solar System. It has a fleet of asteroids and comets that follow it through its orbit – over 2,000 have been discovered – and its great mass means that the centre of gravity for it and the Sun lies above the Sun's surface, meaning they act almost like a binary system. The giant planet's gravity well also means it can intercept comets and asteroids heading into the inner Solar System, and may partially shield the inner planets from bombardment. Another theory, however, is that it actively draws small bodies in from the Kuiper Belt. Whichever is true, Jupiter experiences 200 times more impacts than Earth.

Visible with the naked eye from Earth, Jupiter represented the god Marduk to the Babylonians, and it was Phaethon to the ancient Greeks. The Romans assigned it to their king of the gods, whose name it bears today, whereas to Hindu astronomers it was Brihaspati, or Guru, which means 'heavy one'. Across Asia, it was known as the Wood Star, a name taken from the Chinese theory of the five elements.

Galileo discovered Jupiter's four largest moons, known as the Galilean moons, in 1610, the first time moons had been observed around another planet. Humanity has since explored the planet with observatories and space probes, beginning in 1973 with a flyby by Pioneer 10. Many missions to the outer Solar System have used Jupiter's gravity as a slingshot to correct their course or gain speed, but the first craft to orbit the planet was the aptly named Galileo in 1995.



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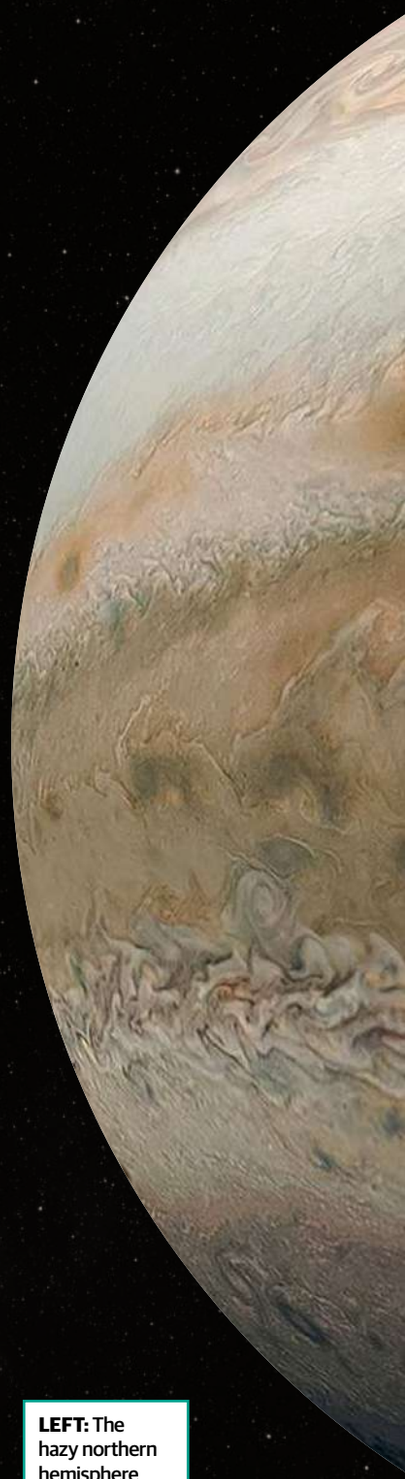
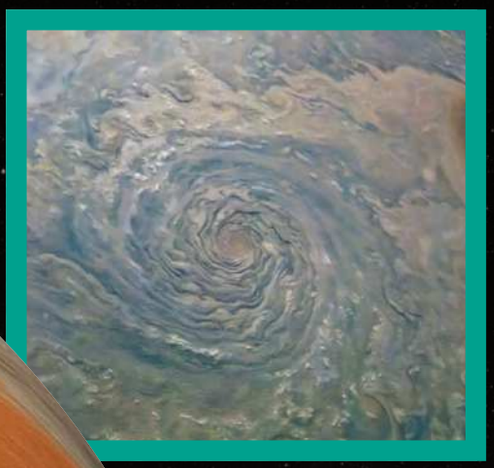


LEFT: The hazy northern hemisphere of Jupiter processed by citizen scientist Gerald Eichstädt from Juno camera data in 2020



ABOVE: A cyclonic storm in Jupiter's northern hemisphere, captured by Juno in 2019

BELOW: Pioneer 10 was the first human-made probe to cross the asteroid belt and fly past Jupiter

ATMOSPHERIC COMPOSITION

UPPER ATMOSPHERE

90% HYDROGEN

10% HELIUM

INTERIOR

71% HYDROGEN

24% HELIUM

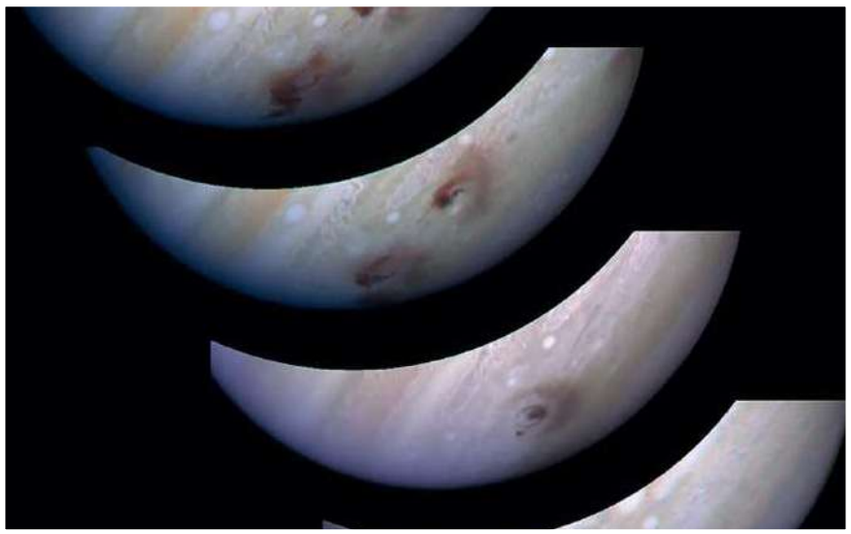
5% OTHER ELEMENTS

NEWS FROM JUPITER

WIND SPEEDS MEASURED

For the first time, scientists have been able to directly measure the winds in the middle of Jupiter's atmosphere. Using the Atacama Large Millimeter/submillimeter Array (ALMA), a team of astronomers was able to track the movement of molecules of hydrogen cyanide in the planet's famously turbulent atmosphere, measuring narrow bands of wind at up to 1,448 kilometres (900 miles) per hour. The hydrogen cyanide is not native to Jupiter, but was added to the storms when comet Shoemaker-Levy 9 collided with the giant planet in 1994. Since then, it has been circling the atmosphere.

"The most spectacular result is the presence of strong jets, with speeds of up to 400 metres [1,312 feet] per second, which are located under the aurorae near the poles," said Thibault Cavalié of the Laboratoire d'Astrophysique de Bordeaux in France, who led the team behind the discovery. Using 42 of ALMA's 66 high-precision antennae, the team measured the Doppler shift, tiny changes in the radiation emitted by the molecules, from which they were able to deduce wind speed.



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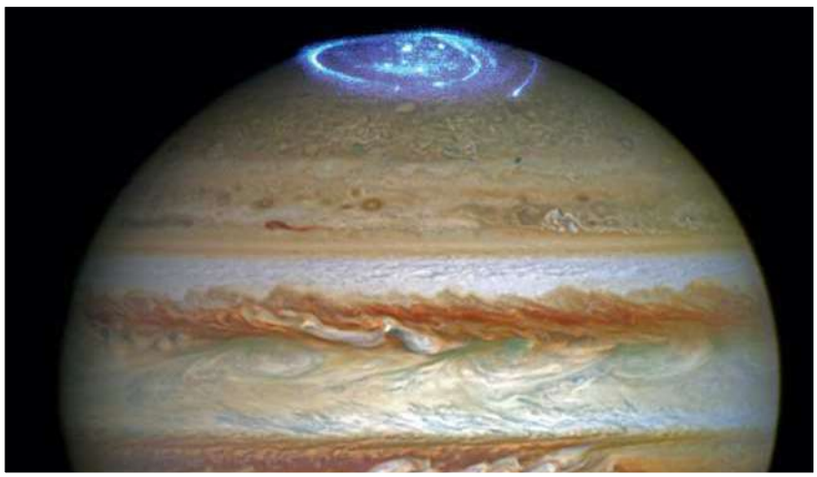

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AURORAL ACTIVITY

Jupiter's version of the northern lights has puzzled scientists, because it doesn't behave like the aurorae on Earth. Here, the lights appear in a ring between 60 and 70 degrees north or south of the equator. Within that ring, an area known as the 'polar cap', the lights don't appear. On Jupiter, however, there is no 'polar cap' – the aurora continues its display all the way to the pole.

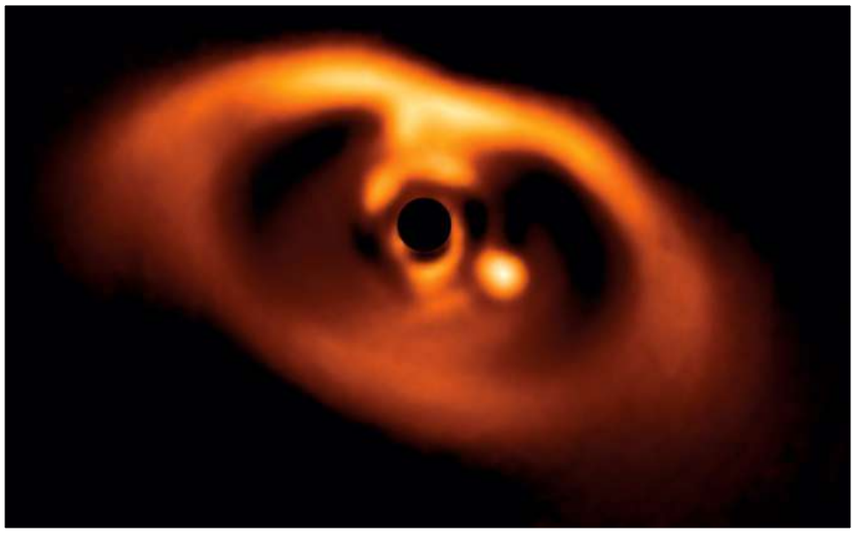
This turns out to be due to a strange quirk of Jupiter's magnetic field. On Earth, the aurorae appear on closed field lines, which extend outwards from the planet before bending back again. Inside the 'polar cap' the field lines are open – they extend out into space – and there are no aurorae. Jupiter, meanwhile, has a mixture of open and closed field lines as you approach its poles, meaning the aurorae are still able to appear.

"We as a community tend to polarise, and couldn't imagine a solution where it was a little of both," said Peter Delamere, professor of space physics at the University of Alaska Fairbanks' Geophysical Institute.

ANOTHER JUPITER

Little is known about how planets as large as Jupiter form, but a planet circling another star under the watchful eye of the Hubble Space Telescope could give us a lot of information. Known as PDS 70b, the planet orbits a young orange dwarf 370 light years away in the southern constellation of Centaurus, which has two actively forming planets within its protoplanetary disc. PDS 70b is already around five times the mass of Jupiter and is possibly twice as large, and at a mere 5 million years old, it should continue to form for a while yet.

"This system is so exciting because we can witness the formation of a planet," said Yifan Zhou of the University of Texas at Austin. "This is the youngest bona fide planet Hubble has ever directly imaged; observations allowed us to estimate how fast the planet is gaining mass." Magnetic field lines turn out to play a role in the formation of such a planet, extending from the disc of dust and gas that surrounds the young star and funnelling material onto the planet's surface.



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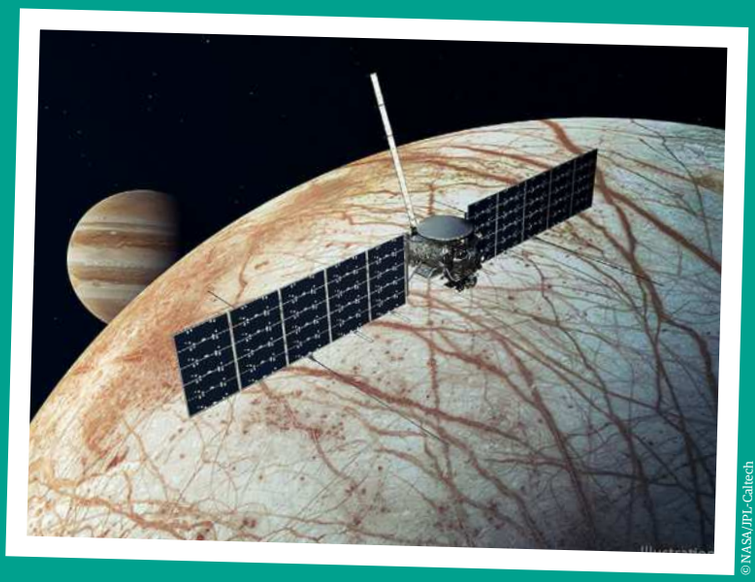
FUTURE PLANS FOR JUPITER

While Jupiter has been heavily photographed by missions such as Juno, which arrived at the planet in 2016, much scientific interest has now transferred to the planet's moons, which are thought to harbour subsurface liquid oceans and possibly even life. Europa, Ganymede and Callisto, three of the Galilean moons, would be the targets, but multiple missions have been cancelled due to a lack of budget.

In 2024 NASA's Europa Clipper should launch, following up on studies from the Galileo probe and performing multiple flybys of Europa without orbiting it, using the gravity of nearby moons to change its course. The European Space Agency will send its Jupiter Icy Moons Explorer (JUICE) in 2023 to study Ganymede, Callisto and Europa, evaluating their potential to support life. Other countries also have their eyes on the giant planet, with China's Gan De proposed for launch in 2029 and an unnamed Russian proposal to use a nuclear-powered tug to travel to the planet sometime after 2030.

Further into the future, Europa is seen as a potential site for human colonisation of the Solar System, as it is geologically stable and levels of radiation are low there. Low is a relative term, however, as unshielded colonists would receive 5.4 sieverts of radiation per day from Jupiter, compared to 0.0024 sieverts per year on Earth. This is still enough to cause radiation poisoning.



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ABOVE: Europa is the target of many space agencies, which are keen to explore its life-hosting potential

EVOLUTION OF THE JOVIAN GIANT

- **Date:** 4.6 billion years ago
  Activity: The Solar System began to form from a cloud of gas and dust around a new star
- **Date:** 4.596 billion years ago
  Activity: Jupiter and Saturn began to take shape
- **Date:** 2400 BCE
  Activity: Babylonians tracked a full cycle of Jupiter's movement across the skies
- **Date:** 270 BCE
  Activity: Jupiter was part of Aristarchus of Samos' heliocentric model of the Solar System
- **Date:** 1610
  Activity: Galileo discovered the Galilean moons: Ganymede, Callisto, Io and Europa
- **Date:** 1892
  Activity: Edward Emerson Barnard discovered a fifth moon of Jupiter, Amalthea
- **Date:** December 1974
  Activity: Pioneer 11 passed within 42,500 kilometres (26,400 miles) of Jupiter's cloud tops
- **Date:** January 1979
  Activity: Voyager 1 reached the gas giant planet
- **Date:** December 1995
  Activity: The Galileo probe entered Jupiter orbit
- **Date:** July 2016
  Activity: The Juno probe entered a polar orbit around the planet

JUPITER BY NUMBERS

24,000°C
The estimated temperature at Jupiter's core

11.8 YEARS
Jupiter's orbit around the Sun

5,000KM
The thickness of Jupiter's atmosphere, the deepest in the Solar System

79
Known moons circulate around Jupiter

1665
Jupiter's Great Red Spot is a storm known to have existed since at least 1831, and maybe even since 1665

14x
Jupiter's magnetic field is 14 times stronger than Earth's, and the strongest in the Solar System except for sunspots

4TH
Fourth-brightest object in the sky as seen from Earth

"MUCH SCIENTIFIC INTEREST HAS NOW TRANSFERRED TO THE PLANET'S MOONS"

MOON PROFILE

EUROPA

ONE OF THE SOLAR SYSTEM'S FAMOUS OCEAN WORLDS IS AN EXCITING PROSPECT FOR FURTHER EXPLORATION

Europa is one of the four Galilean moons that orbit the Solar System's largest planet, Jupiter. Although Europa is the smallest of its satellite siblings – Io, Callisto and Ganymede, carrying on in that order from smallest to largest – it is certainly the one with the most potential for exciting scientific discovery. Underneath its icy, scarred surface could lie a salty ocean, just like the oceans that make up 71 per cent of the Earth's surface.

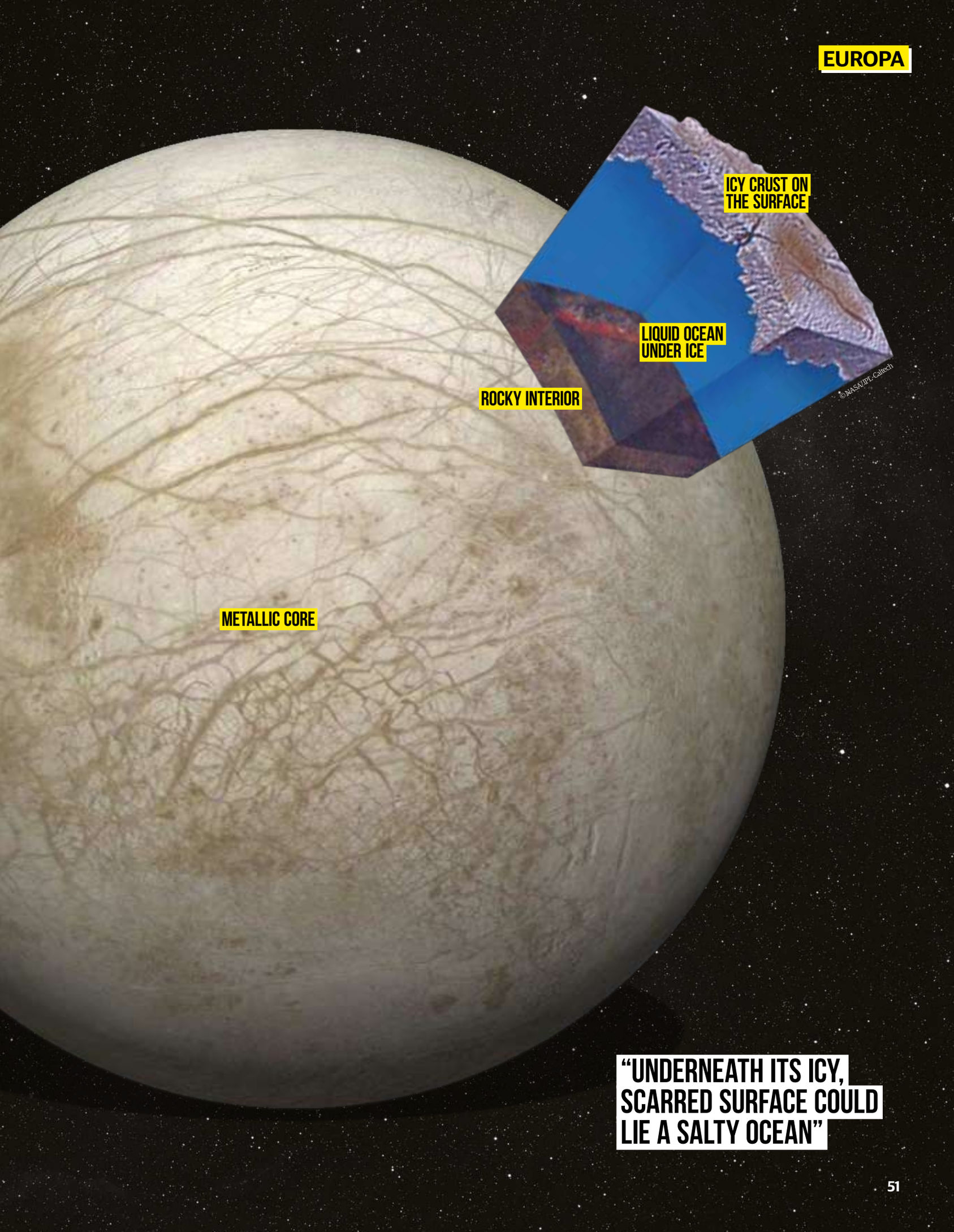
The Galilean moons were discovered in 1610 by Italian astronomer Galileo Galilei, and through the ages, astronomers have been fixating their telescopes on the speck of light that orbits Jupiter once every three-and-a-half days. Europa is also tidally locked to Jupiter, meaning that the same face of the moon is pointing at the Jovian giant at all times, much like the Moon and Earth. Another similarity is the two moons' sizes: Europa has an equatorial diameter of 3,100 kilometres (1,940 miles), which is 90 per cent of the Moon's diameter. If you were to replace the Moon with Europa in our sky, to the naked eye they would both seem about the same size. However, Europa would be much brighter on account of its surface ice reflecting 5.5 times more sunlight than the Moon.

The process behind the creation of Jupiter's largest moons is still hotly debated, but astronomers largely agree that they formed from leftover debris from the formation of Jupiter roughly 4.5 billion years ago. Fast-forward to today and Europa is a water-ice ball with fractures criss-crossing all over the surface. The number of craters currently found all over its cracked terrain indicate that the moon is no older than 90 million years old, suggesting there is likely to be some form of surface replenishment that also brings salts and sulphur compounds to the outer layer. Surrounding the icy world is a thin atmosphere, composed of molecular oxygen.

The core is most likely made of iron, surrounded by a tough, rocky mantle. In between that and the icy crust is a suspected body of liquid. Some may wonder how such a small world, so far away from the heat of the Sun, can maintain an ocean of salty water similar to Earth's. The answer is that it's likely due to the grand gravitational effects of Jupiter, pulling and pushing the insides of Europa, causing it to heat up and, in turn, transforming ice into water. This process is known as 'tidal heating', and it can be observed happening with grander effect on Europa's fellow moon, Io – its interior is heated up to such an extent that volcanoes have popped up.

This tidal heating is what maintains the ocean and provides the energy to replenish the surface via the outburst of plumes or a form of icy plate tectonics. Ever since astronomers became aware of the vitalising interior of Europa, they have pieced together that it has the fundamental building blocks for life to exist: liquid water, chemical compounds for consumption and an energy source. For this reason especially, planetary scientists are excited to return to the Galilean moon. There is a high chance that life could exist in this part of the Solar System, even if it's just in the form of simple microbes.

LEFT: This shows almost-pure water ice, shown in white, broken up by contaminated water ice, shown in red



"UNDERNEATH ITS ICY, SCARRED SURFACE COULD LIE A SALTY OCEAN"

NEWS FROM EUROPA

TABLE SALT FOUND SPRINKLED ON THE SURFACE

Europa has had visitors in the past, notably NASA's Voyager and Galileo spacecraft. On their flybys of the moon, analyses showed that the icy crust consisted of water ice and a substance originally thought to be magnesium sulphate. After recently revisiting the surface using the W. M. Keck Observatory based in Hawaii and the Hubble Space Telescope, astronomers now know that it wasn't magnesium sulphate and was actually sodium chloride – more commonly known as table salt.

As Voyager and Galileo had only an infrared spectrometer to work with, they couldn't see what was hiding in the visible light spectrum. Keck and Hubble, however, were able to unveil the hidden secret. "We thought that we might be seeing sodium chlorides, but they are essentially featureless in an infrared spectrum," highlights Mike Brown, the Richard and Barbara Rosenberg professor of planetary astronomy at Caltech in Pasadena, California.

It was some laboratory tests by Kevin Hand at NASA's Jet Propulsion Laboratory, also in Pasadena, that revealed that irradiating ocean salts under Europa-like conditions exhibit distinct features and a yellowish colour – table salt exhibits this colour on the surface of Europa, confirming its presence.

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SETBACKS FOR EUROPA'S NEXT EXPLORER

NASA has its sights set on sending two very ambitious missions to Europa, one of which is due to launch in 2024. Unfortunately the Europa Clipper mission, an orbiter that will spend about three years at the moon, and the proceeding Europa Lander mission seem to have come under scrutiny after a nine-month investigation concluded that there are serious issues that need to be addressed in order to satisfy both NASA and the United States Congress.

"Our audit found that despite robust early stage funding, NASA's aggressive development schedule, a stringent conflict-of-interest process during instrument selection, an insufficient evaluation of cost and schedule estimates and technical workforce shortages have increased instrument integration challenges and development risks for the Clipper mission," John Schultz, a management analyst at the Office of Inspector General, said in a statement.

After finding these conflicts of interest and issues in the budget, the investigation team have concluded that ten changes should be made in order to get the project back on track, including altering the overall staffing regime, rescheduling milestones and making sure that any estimates be made in accordance with other projects.

STRUGGLING TO FIND THE PLUMES

Europa is a moon that shares many similarities with Saturn's moon Enceladus – both are icy worlds that exhibit signs of a subsurface ocean that could harbour potential life. One major difference though is that Enceladus has been studied much more thoroughly, courtesy of NASA's Cassini mission. In this close-up analysis, Cassini detected plumes of material emerging from the surface of Enceladus, along with a distinct temperature spike in the data to match. However, this doesn't appear to be the same for Europa.

"We searched through the available Galileo thermal data at the locations proposed as the sites of potential plumes. Reanalysis of temperature data from the Galileo mission does not show anything special in the locations where plumes have possibly been observed. There are no hotspot signatures at either of the sites," says Julie Rathbun, a senior scientist at the Planetary Science Institute. "This is surprising because the Enceladus plumes have a clear thermal signature at their site of origin, so this suggests that either the Europa plumes are very different, or the plumes are only occasional, that they don't exist or that their thermal signature is too small to have been detected by current data."

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THE PAST AND FUTURE OF EXPLORATION

Being part of the Jovian system has its benefits in terms of exploration. Although Europa hasn't had the same close inspection as Enceladus, many spacecraft have made a flying visit near to the intriguing satellite as they use Jupiter's enormous mass to provide a 'gravity assist' – when a spacecraft uses a planet's mass to slingshot it to a faster speed.

The first of these visits began with NASA's Pioneer 10 and 11 in 1973 and 1974 respectively. Afterwards came the two Voyager spacecraft in 1979, sending back pictures of Europa's icy surface in stunning resolution. This began speculation that the moon had a subsurface ocean, gathering traction when NASA's Galileo spacecraft spent eight years at the Jovian system, starting in 1995. This long-duration study revealed a host of exciting new discoveries about Europa and its fellow moons. The last spacecraft to visit Europa was NASA's New Horizons in 2007 when it tested its equipment at the Jovian system on the way to Pluto. The future is very exciting for the Galilean moons. Two major space exploration organisations, the European Space Agency (ESA) and NASA, are looking to visit. Due to launch in June 2023 is the ESA's Jupiter Icy moons Explorer (JUICE), which will head to the system in order to study Ganymede, Callisto and Europa. The following year – assuming there are no delays from the aforementioned investigation – NASA will launch its Europa Clipper, solely focused on studying Europa.

After much discussion, the Europa Clipper team decided that, due to Jupiter's radiation, it would be best to put the orbiter in an elliptical orbit that makes 45 close flybys over the course of roughly three years. In a separate mission, there will be a Europa Lander that will complement the Europa Clipper.

NASA'S TIMELINE OF EUROPA VISITORS

- **Date:** 3 December 1973
  Spacecraft: Pioneer 10
- **Date:** 3 December 1974
  Spacecraft: Pioneer 11
- **Date:** 5 March 1979
  Spacecraft: Voyager 1
- **Date:** 9 July 1979
  Spacecraft: Voyager 2
- **Date:** 8 December 1995 to 21 September 2003
  Spacecraft: Galileo
- **Date:** 28 February 2007
  Spacecraft: New Horizons

EUROPA FACTS

671,100 KM
Europa orbits Jupiter at a distance of 671,100 kilometres (417,000 miles), almost double that of the Earth-Moon distance

Europa is the smoothest object in the Solar System, lacking more craters and mountains than any other object

Europa's surface temperature at the equator never reaches higher than -160 degrees Celsius (-260 degrees Fahrenheit)

-160°

Hydrothermal vents could exist on the seabed of Europa, similar to what is seen on the floor of Earth's oceans – a region where extremophiles thrive

All of Jupiter's moons are named after the lovers of Zeus from Greek mythology; Europa was the queen of Crete

The cracks on the surface of the moon are thought to be from the constant movement of the subsurface sea when it gets too close to Jupiter

Europa is stuck in an orbital resonance with two fellow Galilean moons; for every orbit Ganymede completes, Europa does two and Io completes four

TOP LEFT: Europa is one of the most reflective objects in the Solar System because of its icy surface

ABOVE: The New Horizons space probe passed Europa in 2007 on its way to Pluto

PLANET PROFILE

SATURN

SATURN IS FAMOUS FOR ITS RINGS, BUT THERE IS MORE TO IT THAN MEETS THE EYE

The 'Ringed Planet' is not only a fan favourite among astronomers because of its consistent visibility in the night sky, but also because it offers an enticing uniqueness. Along with Jupiter, Uranus and Neptune, Saturn is one of the gas giants - also known as the Jovian planets - that sit in the outer regions of the Solar System. What is most intriguing about the two largest planets in our Solar System - Jupiter and Saturn - is that they are the bridge to understanding stars like our Sun. Although they are classified as planets, they have a more similar composition to the Sun than they do to Earth.

Saturn is one of the brightest objects in the night sky, with an apparent magnitude that swings from -0.55 to +1.17. Magnitude varies with the distances between Saturn, Earth and the Sun. The ringed gas giant is nine times further away from the Sun than Earth is, as well as over nine times the Earth's diameter. As the second-largest planet, Saturn also has an enormous volume capacity - which is capable of fitting 764 Earths inside it.

As it is an extremely bright celestial object, Saturn has been observed for centuries, and as such, its discovery date can't be pinned down. However, the Italian astronomer Galileo Galilei observed Saturn through his telescope in 1610, at first believing that Saturn's rings were actually moons. Over years of observation, the moons would change shape and sometimes disappear, which was due to the planet's inclination with respect to Earth. Galileo's error wasn't realised until 45 years later when Dutch astronomer Christiaan Huygens used a telescope with a higher resolution to resolve the rings.

In modern times space probes have been able to get a much closer look at the planet and its ring structure, the most prominent example being NASA's Cassini spacecraft. Cassini's flybys showed that Saturn's rings are made up of mostly water-ice particles and some rocky meteoroids, sized from tiny grains of sand to as large as mountains and extending up to 282,000 kilometres (175,000 miles) from the planet.

There is much more to Saturn than just its rings, though. It has 53 confirmed moons, with a further 29 provisional moons that are just awaiting confirmation. The most intriguing moons are Titan and Enceladus, which exhibit exciting astrobiological prospects. Titan shows Earth-like weather cycles and lakes, but with hydrocarbons, and Enceladus has a subsurface ocean of liquid salty water. Saturn in itself is an enormous and fascinating structure that has become more and more understood since the days of Galileo and Huygens.

As mentioned previously, Saturn is more similar to the Sun than it is to the Earth. The planet's composition is 94 per cent hydrogen and six per cent helium, with trace amounts of methane and ammonia. While astronomers can't physically dig down into Saturn and see its internal structure, they can build computer models showing how the planet formed 4.6 billion years ago. These models show that as temperatures and pressures rise as you get closer to the core, gaseous hydrogen is squashed into liquid metallic hydrogen. At the core of Saturn is a rocky ball of denser elements, including iron and nickel.

"SPACE PROBES HAVE BEEN ABLE TO GET A MUCH CLOSER LOOK AT THE PLANET AND ITS RING STRUCTURE"

ABOVE: The Cassini space probe spent 13 glorious years scrutinising the Saturnian system

BELOW: This is the famous image titled 'The Day the Earth Smiled'

METALLIC HYDROGEN

ROCKY IRON CORE

MOLECULAR HYDROGEN

SATURN COMPOSITION

94%
HYDROGEN

6%
HELIUM

+
TRACES OF AMMONIA AND METHANE

NEWS FROM SATURN

TITAN SURVIVED SATURN'S ANCIENT FEEDING FRENZY

It's likely that when Saturn was in its younger years, it was accreting whatever mass it could to become the enormous size it is now. In this primordial feeding frenzy, natural satellites orbiting close to the surface were likely engulfed on account of Saturn's gravity. Yet Titan, the second-largest natural satellite in the Solar System behind Jupiter's Ganymede, has remained in orbit.

Yuri Fujii, a designated assistant professor at Nagoya University, and Masahiro Ogihara, a project assistant professor at the National Astronomical Observatory of Japan (NAOJ) have recently proposed that Titan was spared from this frenzy due to a 'safety zone' created by the warmer and closer gas. In this scenario, the inner gas pushes a large moon away from Saturn and stops it from being consumed.

"We demonstrated for the first time that a system with only one large moon around a giant planet can form," said Fujii. "This is an important milestone to understand the origin of Titan." Not only does it help explain the origin of Titan, but it also helps explain why Saturn only has one relatively huge moon. The next biggest Saturnian moon is Rhea, which is less than a third the size of Titan.

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WHAT HAPPENS TO SATURN WHEN THE SUN TURNS INTO A WHITE DWARF?

In approximately 5 billion years our Sun will have swallowed the rocky terrestrial planets, including Earth, as it entered the red supergiant phase of its lifetime. After a further 3 billion years, the supergiant star will have shed its outer layers and left behind a white dwarf star. This will be the dense, scorching-hot remnant of the star we know now.

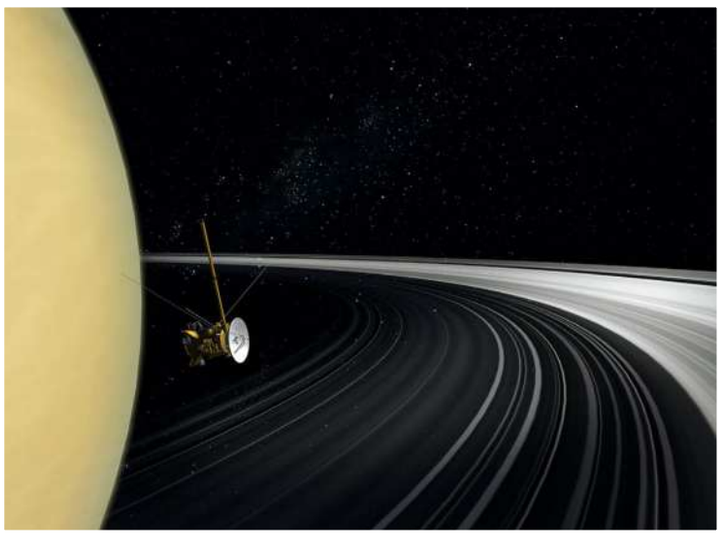
Recent research conducted by Matthias Schreiber, an astrophysicist at the Universidad de Valparaíso in Chile, suggests that once a Sun-like star has transformed into a white dwarf, it would be able to accrete the evaporated layers of its surrounding gas giant planets. This research has very intriguing implications for the future evolution of the Solar System, and in particular the ability to spot signs of Saturn in a white dwarf star.

Schreiber goes more into the details: "The white dwarf will accrete a fraction of the evaporated material, and this will result in detectable signatures, so future generations of alien astronomers, if they exist, can potentially investigate the chemical composition of Jupiter, Saturn, Neptune and Uranus."

LORD OF THE RINGS: THE TWO EXPLANATIONS

The origin of Saturn's rings has been subject to constant debate since their discovery. While some believe they formed during the formation of the planet 4.6 billion years ago, others think they could have arisen within the last couple of hundred million years. Recent research by Aurélien Crida of the Observatoire de la Côte d'Azur argues that they are most likely ancient, based on data taken during the Cassini mission's 'Grand Finale', which consisted of a series of dives through Saturn's rings before vaporising in the atmosphere. During this time, Cassini measured the mass of the ring system as about 15.4 million billion tonnes. That's equivalent to about 40 per cent of the mass of Saturn's moon Mimas, which is 400 kilometres (250 miles) wide.

Some argue that because the rings are more than 95 per cent water ice, they should be more contaminated if they are ancient. However, Crida has provided evidence that suggests the mass of Saturn's rings is consistent with 4.6 billion years of very dynamic evolution. "I think that, objectively, [this theory] forms a much more consistent picture, with a convincing model of their formation at the same time as Saturn, plus formation and outward migration of the satellites in agreement with the observations", said Crida.



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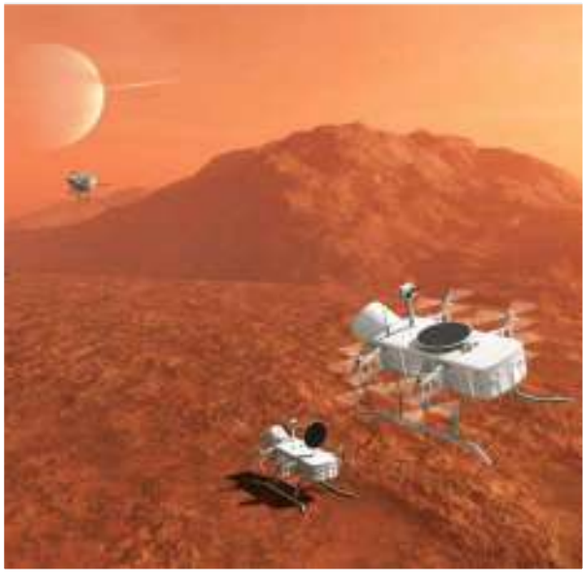
THE HISTORY OF SATURNIAN EXPLORATION

Saturn has been extensively studied across centuries. When Galileo used his telescope in the early 17th century, the rings of Saturn became apparent. Fast forward to today, and there is a host of commercially available telescopes to see the planet in amazing clarity. There is also a team of ground and space-based observatories that frequently capture observations of the planet to provide regular updates.

In regards to space probe missions to Saturn, it has had a handful of human-made mechanical visitors over the last few decades. The first interplanetary investigator was NASA's Pioneer 11 spacecraft; it became the first probe to encounter Saturn on 1 September 1979. After that were NASA's two Voyager probes, which returned historic images of the outer Solar System, discovering moons and revealing surface features that had never been seen before. Voyager 1 flew past Saturn on 12 November 1980 and Voyager 2 followed suit on 26 August 1981.

The most fruitful mission to Saturn arrived there on 1 July 2004. The Cassini space probe – created in a collaboration between NASA, the European Space Agency (ESA) and the Agenzia Spaziale Italiana (ASI) – stayed in orbit around the Ringed Planet for 13 years, and the ESA-built Huygens lander arrived on the surface of Titan on 14 January 2005. For over a decade this probe took magnificent images, collected pivotal data and even took the first dive through the planet's rings. During this 'Grand Finale', as it was known, the space probe was able to collect unprecedented data on the Cassini Division, which is the wide gap between rings A and B.

This mission is still fresh in the memory of astronomers, as they are still examining heaps of data collected during Cassini's stay at Saturn. This means that we're unlikely to see a Saturn-specific mission in the foreseeable future. Do not give up hope, though, as there are certainly talks of returning to its moons. For example, NASA's Dragonfly mission is hoping to launch a drone to the surface of Titan in 2027.



© Adrian Mann

BELOW: The Dragonfly mission will examine Saturn's largest moon, Titan

A TIMELINE OF CASSINI-HUYGENS' VOYAGE TO SATURN

- **Date:** 15 October 1997
  Activity: Cassini-Huygens was launched from Cape Canaveral.
- **Date:** 30 December 2000
  Activity: The spacecraft passed Jupiter to conduct a gravity-assist manoeuvre.
- **Date:** 1 July 2004
  Activity: The Cassini-Huygens space probe arrived at Saturn.
- **Date:** 14 January 2005
  Activity: The Huygens probe separated from Cassini and landed on the surface of the moon Titan.
- **Date:** 19 July 2013
  Activity: Cassini took the historic picture of Earth from Saturn titled 'The Day the Earth Smiled'.
- **Date:** 29 November 2016
  Activity: The Grand Finale began as Cassini dove into Saturn's rings.
- **Date:** 15 September 2017
  Activity: The Cassini mission reached its conclusion in Saturn's atmosphere.

SATURN FACTS

A day on Saturn is about ten hours and 40 minutes, but a year takes 29.5 Earth years

There are seven sections to Saturn's rings, with A, B and C being the main rings, and D, E, F and G the fainter rings

Saturn is tilted nearly 27 degrees with respect to the Solar System's orbital plane. This means the Ringed Planet experiences seasons similar to Earth, which has a tilt of 23.5 degrees

This planet is named after the Roman god of agriculture and wealth, but also the father of Jupiter, Neptune, Pluto, Juno, Ceres and Vesta

On 15 September 2017 the Cassini space probe performed a controlled entry into Saturn's atmosphere as astronomers did not want to contaminate its moons

Due to the perceived inclination of Saturn in relation to Earth, the rings 'disappear' twice every 29-and-a-half years

The magnetic field of Saturn is 578 times more powerful than Earth's and is theoretically powered by the planet's liquid metallic hydrogen layer

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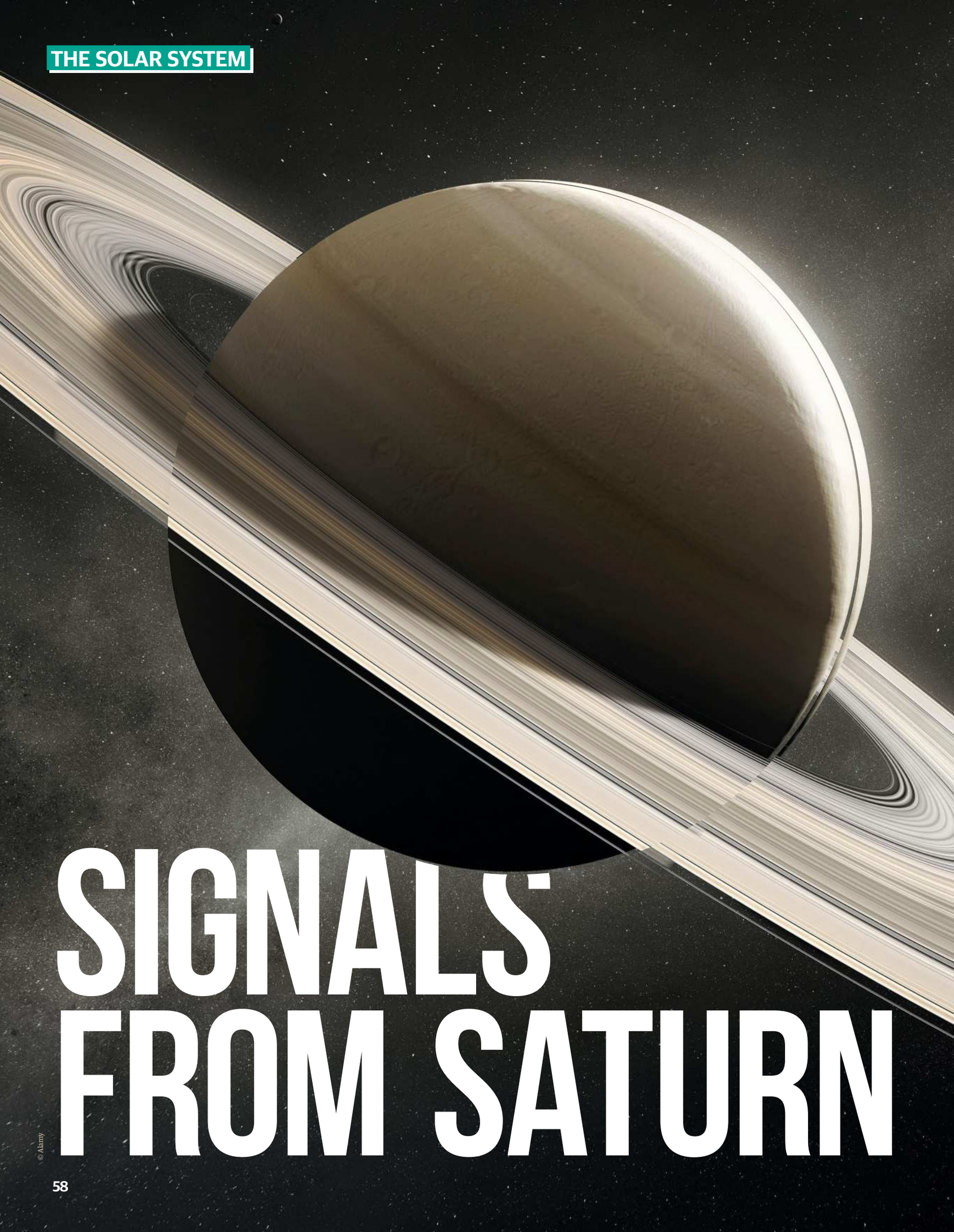


SIGNALS FROM SATURN

AN UNUSUAL SIGNAL FROM THE RINGED PLANET'S MOON RHEA NOW HAS A POSSIBLE EXPLANATION

When NASA's Cassini spacecraft flew past Rhea, Saturn's second-largest moon, it detected an unexpected and puzzling change in the ultraviolet radiation reflected from its surface. The data from Cassini's flybys has led to a range of speculation and possibilities. Dr Amanda Hendrix, an expert in ultraviolet spectroscopy of planetary surfaces at the Planetary Science Institute in California, said that they noticed a dip in the spectrum and wondered if it was caused by some type of water ice. It was certainly an intriguing puzzle.

The signal was detected by the Cassini craft that was launched from Cape Canaveral on 15 October 1997. After seven years of travel it reached Saturn on 1 July 2004, and in total it orbited the planet for over 13 years. When it became very low on fuel it was decided to end the mission, and to avoid biological contamination of the planet or its moons, it was deliberately sent into Saturn's atmosphere, where it burnt up on 15 September 2017.

Cassini is one of the largest ever interplanetary probes to be built, weighing 2,150 kilograms. It carried the European Space Agency's (ESA) Huygens lander probe, which it sent towards Titan, Saturn's largest moon, on 25 December 2004. After 21 days of travel Huygens finally entered Titan's atmosphere on 14 January 2005, and once on its frozen surface it transmitted data for 72 minutes until Cassini went out of range.

Since then scientists have researched this information to investigate the atmosphere of Titan and its geology. They made several important discoveries, including the fact that the levels of methane increased as the craft descended, whereas the amount of nitrogen remained constant. The presence of methane is exciting because it could be produced by micro-organic life, but ESA scientists think it is more likely large amounts of liquid methane are trapped under the surface ice and released into the atmosphere by cryovolcanism.

Besides the Huygens lander, Cassini carried a large array of instruments to study Saturn and its moons. Some of these measured its magnetosphere and the presence of dust particles, and infrared, visible and ultraviolet images were captured using cameras and spectrographs. It was the Ultraviolet Imaging Spectrograph (UVIS) science package that detected the puzzling findings sent back from Rhea. The UVIS included a two-channel system for studying far and extreme ultraviolet light in wavelengths of 55.8 to 190 nanometres (nm).

The light reflected from planetary objects passed through the four UVIS telescopes into a spectrograph, where it was split into its component wavelengths. These wavelengths, invisible to the human eye, were able to show information and images of the night side atmospheres of Saturn and Titan. Hendrix, who analysed this data, said that this ability meant it could 'see' gases that were not seen by Cassini's visible-light cameras. This ultraviolet light also showed patterns that revealed the chemical elements and compounds in the Saturn system. As an example, it identified a plume of material erupting from the south pole of Enceladus as being composed of water.

UVIS could also use an occultation technique to obtain ten times more detail of Saturn's

RHEA BY NUMBERS

1672
Year Giovanni Cassini discovered Rhea

1847
Year it was named by John Herschel

1,528 KM
Diameter of Rhea

-174°C
Maximum surface temperature

-220°C
Minimum surface temperature

1.233
times denser than liquid water

4.518
Days it takes to orbit Saturn

527,068KM
Average distance from Saturn

SATURN'S FAMILY PORTRAIT

The sixth planet from the Sun has a distinctive ring system and at least 82 moons

1 TITAN

The giant of the Saturn family, it is bigger than our own Moon and a little bigger than the planet Mercury, having a diameter of 5,149.46 kilometres (3,200 miles). It takes roughly 16 days to orbit Saturn and permanently presents one side towards the planet.

There is the exciting possibility that primitive life forms might exist in the liquid water ocean that lies beneath the moon's surface. Unlike any other moon in the Solar System, it has a substantial atmosphere that is mostly composed of nitrogen and methane.

2 RHEA

The second-largest moon. The surface is mainly composed of water ice and it has an ice mantle. Its chemical composition and evolutionary history are very like that of Dione. They both have ice cliffs that are caused mainly by tectonic strains that fractured the moons' surfaces. The side of Rhea that always faces away from Saturn has two large impact craters: the 500-kilometre (311-mile) diameter Mamaldi basin and the 360-kilometre (224-mile) diameter Tirawa basin. The impact scar of Tirawa overlaps Mamaldi, indicating that it is geologically younger. The unusual far-ultraviolet radiation from Rhea detected by Cassini, centred near 184 nanometres in the electromagnetic spectrum, was probably caused by hydrazine. How or where it comes from still remains a mystery.

3 DIONE

Although it's smaller than Rhea, it has a higher mass density, which is 1.48 times that of liquid water, indicating it has a silicate rock core surrounded by ice. It might even have a liquid salt water ocean beneath its surface. An outstanding feature of the moon is a bright pattern of icy cliffs that were seen as long, wispy streaks in the images from the Voyager probes.

It has a landscape of craters, tectonic fractures and a tenuous exosphere. Some of the craters are 100 kilometres (62 miles) across, and there is a variety of heavily and lightly cratered plains.

x4 Images © NASA/JPL-Caltech

What is hydrazine?

Hydrazine is a colourless, inorganic liquid that is highly combustible and smells like ammonia. It has similar properties to water in terms of density, surface tension, viscosity and freezing point. It is very toxic and can cause burns and serious damage to vital organs. It is often used to propel thruster motors on spacecraft. They work by hydrazine being exposed to a catalyst, causing the release of heat and gas that is directed out of the engine's nozzle.

rings than Cassini's visible-light cameras. This involved UVIS locking onto a bright star and recording how the ultraviolet light changed when the rings of Saturn or a planetary body passed between them.

The perplexing dip in the far-ultraviolet from Rhea, centred near 184nm, is outlined in Dr R. Mark Elowitz' PhD thesis ***Far-Ultraviolet Spectroscopy of Saturn's Moons Rhea and Dione***. In it he notes that data from Rhea and Dione showed a weak absorption feature near 184nm, and that as early as 2008 it was found that Phoebe presented similar readings. At the time, various ice mixtures of water, tholins, carbon, kerogen and poly-HCN could not explain this feature. Observations of Mimas, Enceladus and Tethys have also revealed absorption spectra in the same region of the spectrum.

To explain the Rhea signal, scientists decided the best route to an answer was to compare the spectra collected by Cassini to the spectra of thin-ice measurements in the laboratory. The far-ultraviolet data was extracted from targeted flybys of Rhea in 2007, 2010 and 2011 using datasets that completely filled the moon's surface and provided the highest signal-to-noise spectra. Elowitz, who was one of the team members, says: "Over 20 modelled spectra of different chemical species of interest to studies of icy moons in the outer Solar System were compared with the Cassini observational data, with only two chemical species representing a good fit to the observed reflectance spectra. Those two chemical species included simple chloromethane molecules and hydrazine monohydrate. To determine the most likely of these two chemical species to exist in the upper surface ice layer on Rhea, the different sources and sinks of each chemical compound were explored, including the various chemical pathways that could lead to their production."

Considering the two possible chemical compounds, it was determined that simple chloromethane compounds are least likely to be the answer. As Elowitz notes: "It would require the presence of a deep subsurface ocean under the ice shell of Rhea. It is unlikely the chloromethane compounds or salt derivatives of these compounds could migrate upwards through tiny cracks or fissures over hundreds of kilometres to the surface."

The only other possible source of chlorine is via exogenic delivery by chondritic asteroids or micrometeoroids throughout the history of Rhea. If these simple chloromethane compounds were scattered over Rhea in this manner, they would produce by-products on the surface ice of Rhea. These chemical by-products were not found, so this possibility had to be ruled out.

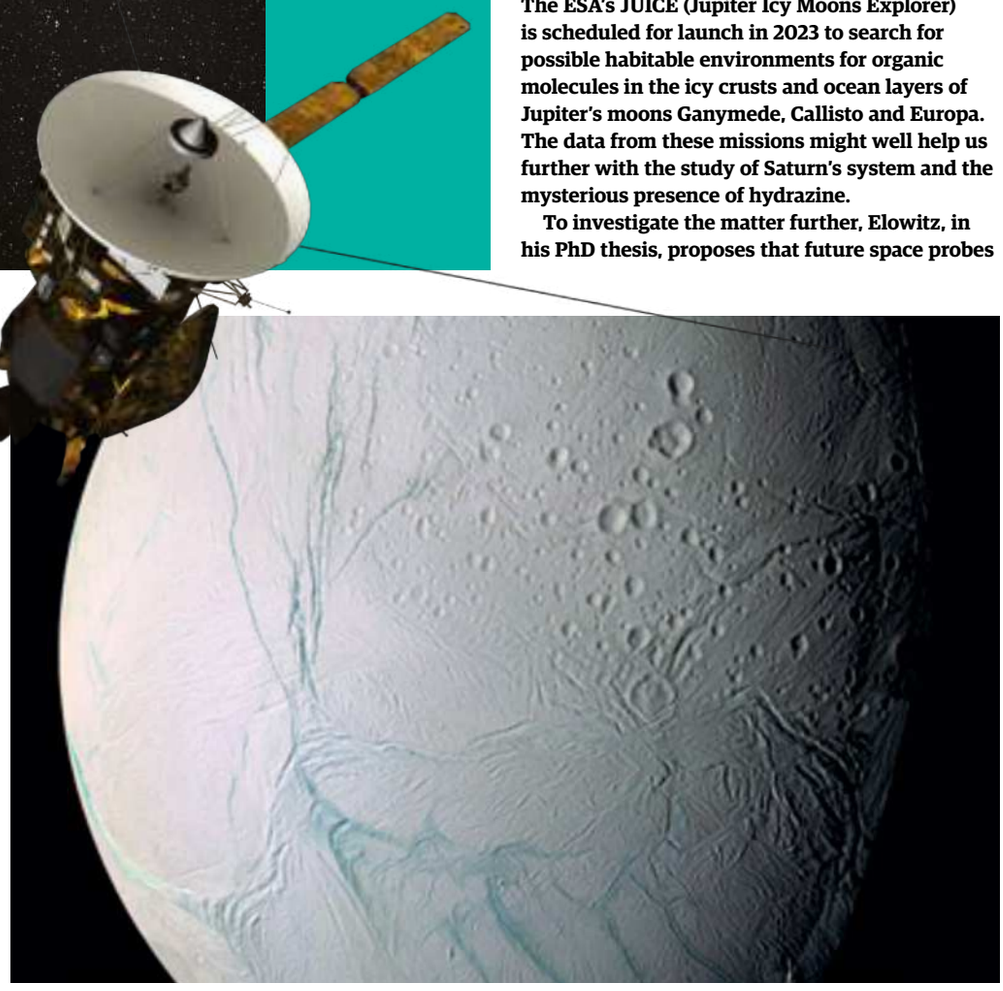
That left the researchers having to explain why hydrazine monohydrate was detected. One immediate possibility was that the Cassini craft itself produced the hydrazine, as it was equipped with a 132-kilogram tank of hydrazine that fuelled its 16 attitude and small trajectory thruster motors.

Professor Nigel Mason, head of the School of Physical Sciences at the University of Kent and a co-author, along with Elowitz and Hendrix, of the science paper ***Possible Detection of Hydrazine on Saturn's Moon Rhea***, says: "We looked at spectra of other moons, like Dione and Tethys, since if

4 TETHYS

It is an irregular ball of ice with a diameter of 1,066 kilometres (662 miles). It has a high level of reflectivity, indicating it is mainly composed of water ice. It is similar to Dione and Rhea, except it is less cratered. The crater floors reflect a lot of light, suggesting the presence of water ice, and further reflectivity is caused by water-ice particles from Saturn's E-ring that erupt from geysers on Enceladus and end up showering Tethys. It has two noteworthy features: the Ithaca Chasma, a 1,930-kilometre (1,200-mile) long crack along its surface that covers 75 per cent of its circumference, and the 445-kilometre (276-mile) Odysseus crater that dominates the western hemisphere. It's possible that its impact helped create the Ithaca Chasma.

BELOW: A mosaic view of the moon Enceladus using spectral filters, taken by Cassini's narrow-angle camera



the signal was present on all moons it might suggest we should look for a common source, for example spacecraft fuel contamination of the spectrometer. The data from Tethys showed no signal, and we looked at other spectra to check for contamination and if the spacecraft motors were firing during or before observation to leave a 'plume' of hydrazine."

The spacecraft's own thrusters seemed a very likely culprit, but they had to be ruled out because they were never fired while Cassini made its flybys of Rhea. And, as Mason points out, hydrazine fuel would have contaminated data gained from other moons and not just showed up when it looked at Rhea.

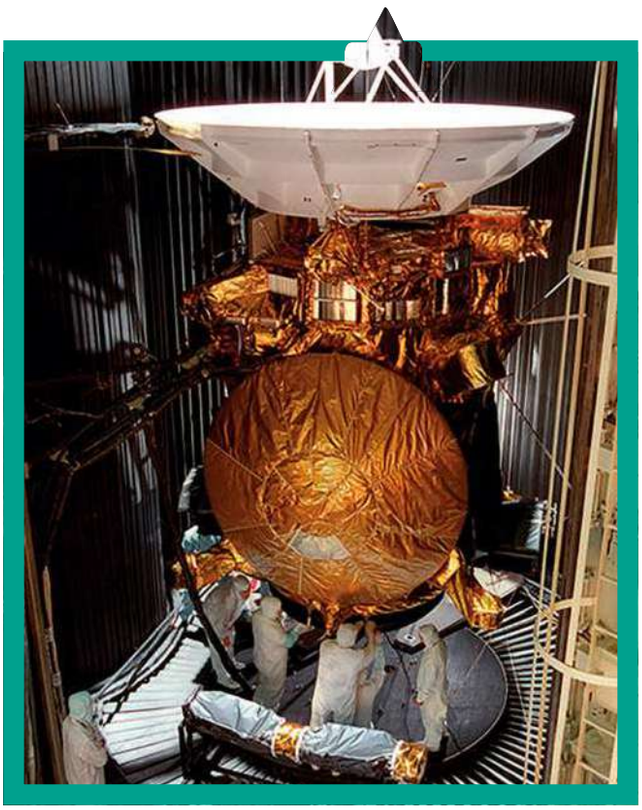
Elowitz explains that if there is ammonia on the icy surface of Rhea, it could produce hydrazine "by irradiation from high-energy particles originating from Saturn's magnetosphere". However, he continues: "An alternative explanation is that hydrazine is produced on Titan from irradiation of ammonia present on its surface and/or atmosphere. The hydrazine then escapes from Titan's atmosphere and is deposited over geologically long timescales on Rhea's upper ice layer."

Hydrazine, therefore, remains the prime candidate to explain the absorption signature seen in the Cassini far-ultraviolet spectral data, though Hendrix says we still need to figure out why this feature has been observed on some of the other moons of Saturn. In her view, it indicates that this process is happening throughout the Saturn system, and possibly elsewhere.

Regarding future studies, Mason says: "We are looking at spectra of other moons, not only to search for hydrazine, but to look for other compounds. The UV spectral database is used to look at other planets and moons, so we are exploring the chemistry of Jovian moons in preparation for the JUICE mission, and hopefully data from the Juno mission now it has been extended. Due to their volcanic nature, sulphur compounds are expected to be formed on those moons, so we are looking for these. Hendrix is also on the New Horizons team with the UV spectrometer, so data from Pluto and Kuiper Belt objects is being analysed as well."

The New Horizons space probe was launched on 19 January 2006 to explore Pluto and the Kuiper Belt. It swung past Jupiter in February 2007 and made its closest approach to Pluto on 14 July 2015. NASA's Juno space probe has been orbiting Jupiter since 5 July 2016, where it has been studying the composition of the planet. The ESA's JUICE (Jupiter Icy Moons Explorer) is scheduled for launch in 2023 to search for possible habitable environments for organic molecules in the icy crusts and ocean layers of Jupiter's moons Ganymede, Callisto and Europa. The data from these missions might well help us further with the study of Saturn's system and the mysterious presence of hydrazine.

To investigate the matter further, Elowitz, in his PhD thesis, proposes that future space probes



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ABOVE: Technicians were dwarfed by the huge Cassini-Huygens craft as they tested it in 1996

should be equipped with infrared and ultraviolet spectrometers to examine the surface of Rhea and the similar icy moons of Saturn. Cassini's UVIS instrument could be improved by employing a hyperspectral imaging system. Each pixel in the multi-layered sensor would obtain spatial and spectral information. The far-ultraviolet spectrum data received by each pixel would identify chemical compounds by reference to their reflective properties, and the whole instrument would be able to create detailed geochemical maps of selected areas of interest. "The detailed spectral maps would be used to characterise the spatial variability of the abundance of hydrazine monohydrate or chloromethane molecules, which could not be performed using the previous Cassini UVIS data due to limitations resulting from low signal-to-noise," notes Elowitz.

The use of advanced spectrometers with higher sensitivities could be used to examine the upper layers of Rhea, Dione and Tethys for the presence of hydrazine monohydrate or chlorine molecules, and it would be great to send landing craft to these moons. The Curiosity rover carried mass spectrometers and gas chromatographs that detected dichloromethane on Mars, so any future surface landers on the icy moons should be equipped with similar equipment to help verify the existence of hydrazine or chloromethane. Certainly, there is plenty more to learn and understand about this fascinating signal.

Nigel Watson
Space science writer
Nigel has written extensively about science and technology, in particular about extraterrestrial contact. He is the author of four books on alien life.

CASSINI SPACECRAFT

1 High-gain antenna
The four-metre (13-foot) wide antenna sent data back to Earth, and variations in the signal helped to study Saturn's atmosphere. The central low-gain antenna had a wider, less powerful range.

2 Magnetometer (MAG)
Two magnetometers were mounted on a boom to detect the strength and distribution of Saturn's magnetic field and its influence on its moons.

3 Radio and Plasma Wave Science (RPWS)
Three ten-metre (33-foot) long antennae were used to detect radio waves and plasma in Saturn's magnetosphere.

4 Remote-sensing pallet
Included wide-angle and narrow-angle cameras along with instruments to study Saturn's electromagnetic spectrum.

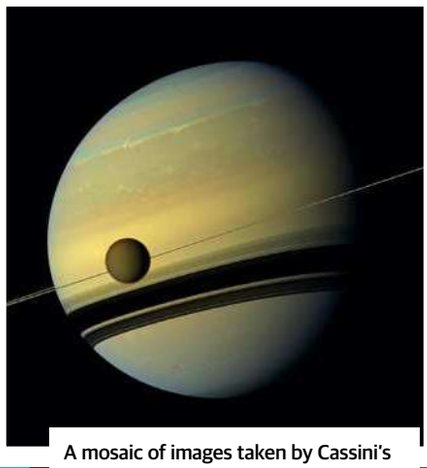
5 Engines
One main engine and an unused back-up engine were used for velocity and trajectory changes. 16 thrusters were used for smaller manoeuvres.

6 Radioisotope thermoelectric generators (RTGs)
Through the decay of plutonium-238, the three RTGs supplied electrical power to the spacecraft and its instruments.

7 Huygens Titan probe
The 318-kilogram craft carried six scientific instruments to the surface of Titan, where it transmitted data back to the orbiting Cassini craft.

8 Fields and Particles pallet
Featured instruments to study cosmic dust, magnetic fields, plasma and gaseous components surrounding Saturn.

9 Radar bay
Using a multi-beam sensor, this was designed to map the surface of Titan and other moons of Saturn and study Saturn's rings.



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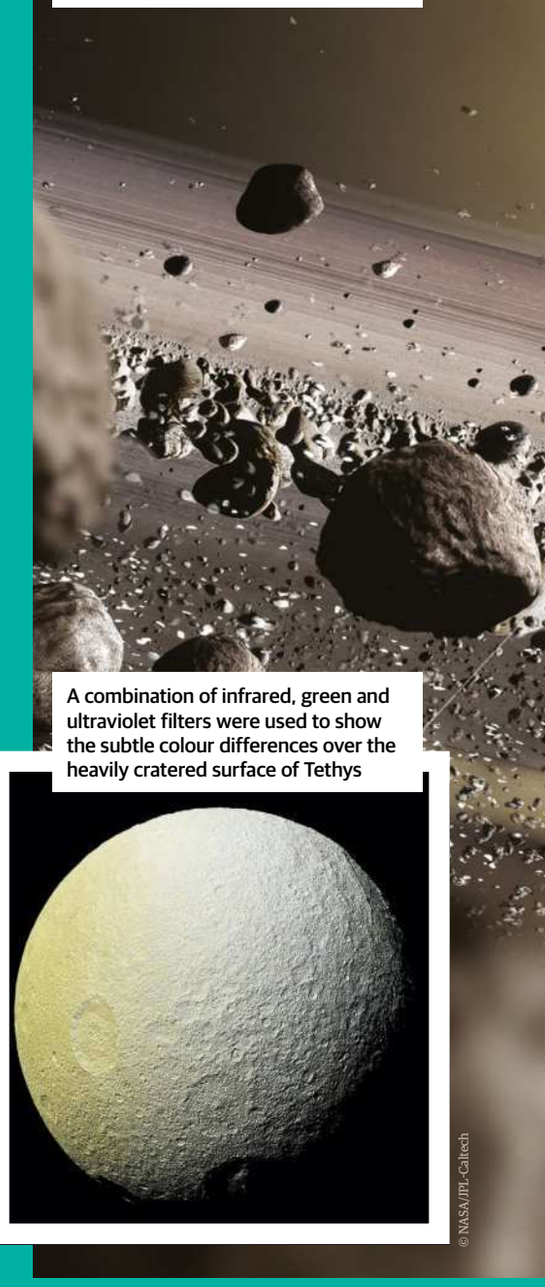
A mosaic of images taken by Cassini's wide-angle camera – using red, green and blue spectral filters – showing Saturn, its rings and Titan



A combination of infrared, green and ultraviolet filters were used to show the subtle colour differences over the heavily cratered surface of Tethys

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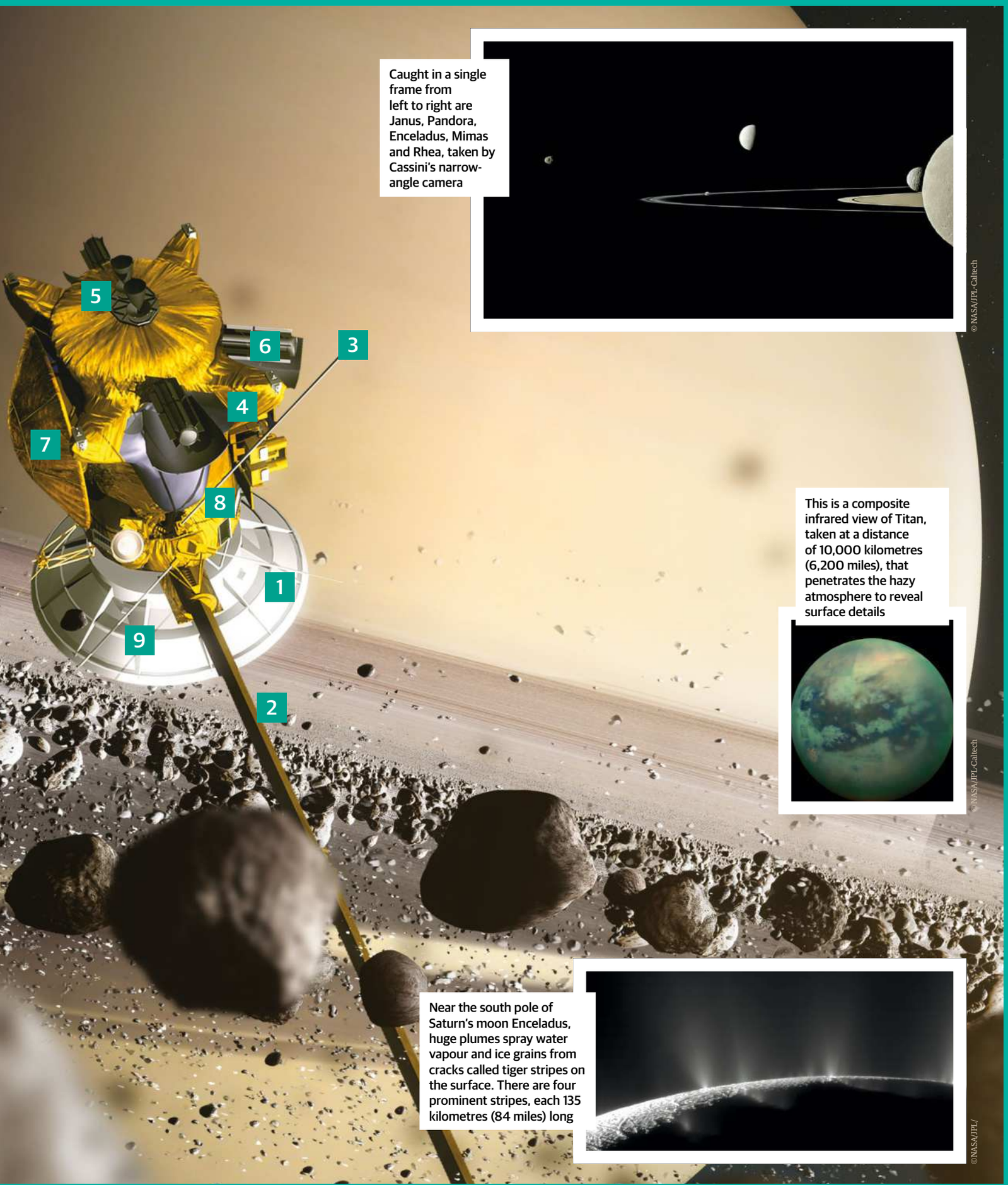


Caught in a single frame from left to right are Janus, Pandora, Enceladus, Mimas and Rhea, taken by Cassini's narrow-angle camera

This is a composite infrared view of Titan, taken at a distance of 10,000 kilometres (6,200 miles), that penetrates the hazy atmosphere to reveal surface details

Near the south pole of Saturn's moon Enceladus, huge plumes spray water vapour and ice grains from cracks called tiger stripes on the surface. There are four prominent stripes, each 135 kilometres (84 miles) long

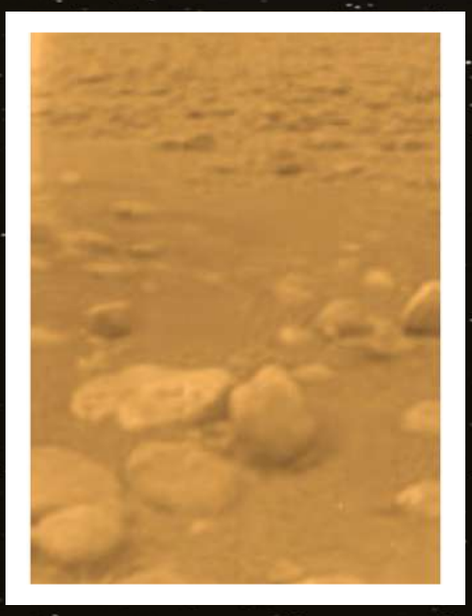
MOON PROFILE

TITAN

SATURN'S MOON IS A HARSH, UNINHABITABLE WORLD, YET HAS UNCANNY SIMILARITIES TO OUR HOME PLANET

Titan is one of the most intriguing moons in our Solar System. From the outside, astronomers see a ball of golden-orange haze, but it's what's hiding beneath this atmosphere that intrigues many – a freezing world with bodies of liquid. Planetary scientists are fascinated by Titan and its unusual contents.

Titan, the largest moon of Saturn and second-largest moon in the Solar System behind Jupiter's Ganymede, is an icy ball that stretches out to almost 5,150 kilometres (3,200 miles) in diameter, nearly 50 per cent wider than the Earth's Moon. Due to Saturn's position, which is around 1.4 billion kilometres (870 million miles) from the Sun, nine-times farther than Earth's average distance, its satellite Titan receives sunlight that is 100-times fainter than the light on Earth. This freezing world may be one that is inhospitable for humans, but there are bodies of liquid present on the surface. These observations have been the subject of many studies throughout the decades.



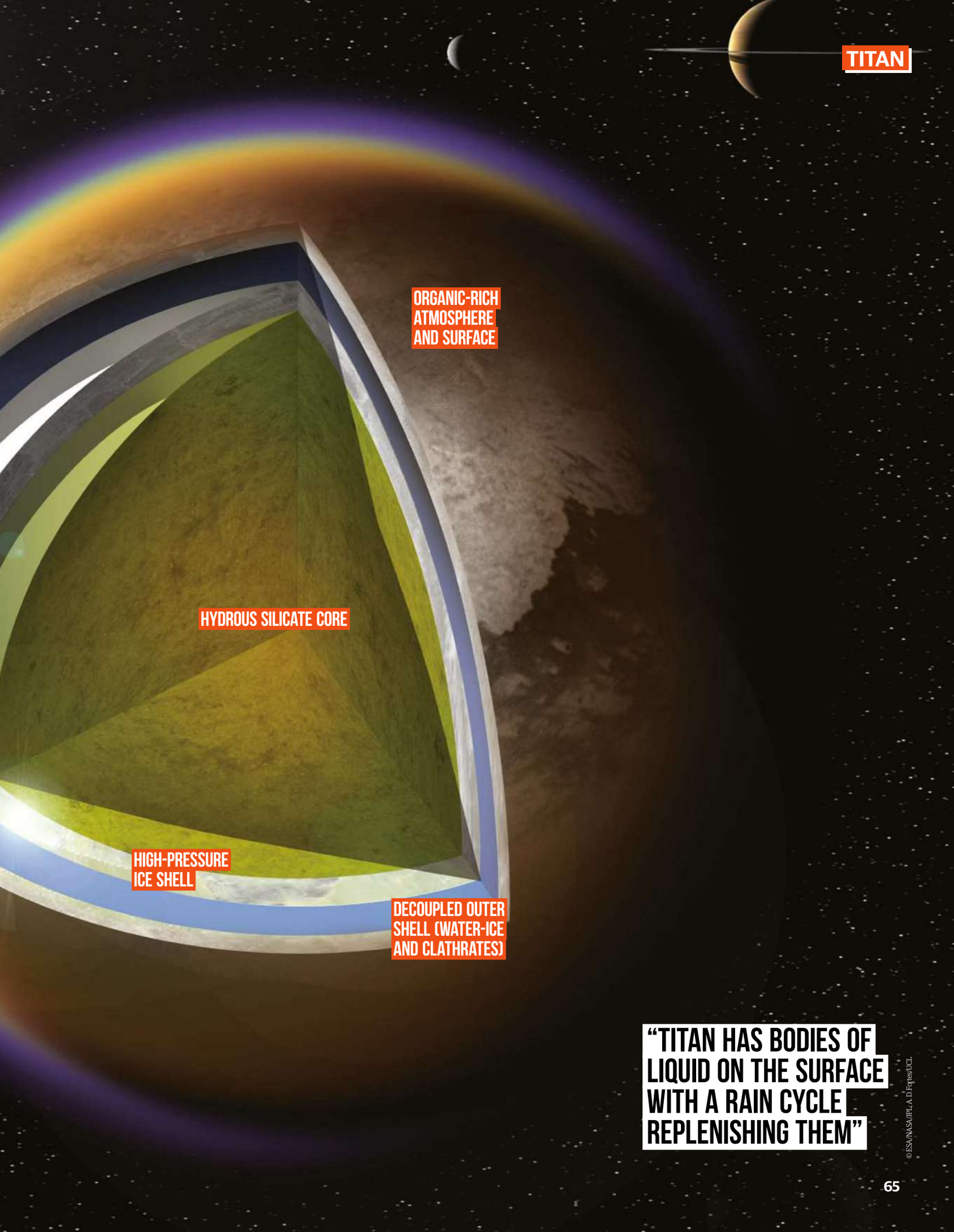
Although there are many interesting moons in the Solar System, Titan is the most Earth-like: it has an atmosphere and it is rocky, but also has bodies of liquid on the surface with a rain cycle replenishing them. All of this happens on a moon that has a surface temperature of minus 179 degrees Celsius (minus 290 degrees Fahrenheit); there obviously isn't water on Titan as that would have been frozen. These lakes, rivers and seas are filled with hydrocarbons such as methane and ethane. These complex molecules are capable of existing as a liquid in such a cold temperature.

As for the atmosphere – in fact, Titan is the only moon with a thick atmosphere in the Solar System – it has an atmospheric pressure 60 per cent greater than that of the Earth. This would feel the same as swimming 15 metres (50 feet) below the surface in an ocean on Earth. This atmosphere is comprised mostly of nitrogen, with a whopping 95 per cent. Around five per cent is methane and the extremely small remainder is carbon-rich compounds. This provides the orange haze that is seen from afar.

The presence of an atmosphere and surface liquid means there is a cycle of evaporation and condensation, creating clouds of methane ice and cyanide gas and precipitation in the form of methane rain. A moon with a weather cycle is unusual, and astronomers are amazed at how the Earth's water cycle can be applied to a distant, alien world.

There is a mystery about Titan that astronomers can't seem to explain with any conviction, and that's what is replenishing Titan's atmosphere. It is known that sunlight breaks up methane at the top of the moon's atmosphere, and scientists are wondering what is bringing more methane into the atmosphere in its place. One suggestion has been volcanic activity. The presence of volcanoes would be yet another amazing similarity between Titan and our home planet.

LEFT: The Huygens lander sent back images of the Titanian surface to Cassini



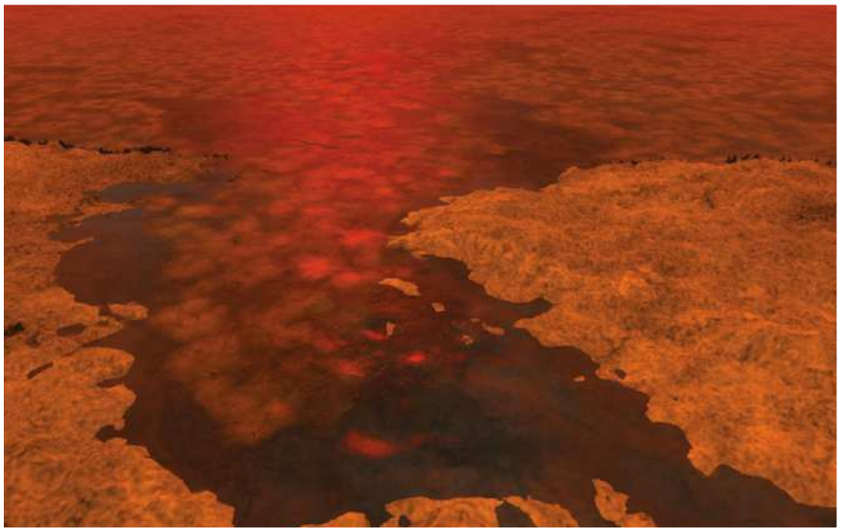
"TITAN HAS BODIES OF LIQUID ON THE SURFACE WITH A RAIN CYCLE REPLENISHING THEM"

NEWS FROM TITAN

UNDERSTANDING THE ATMOSPHERE

Titan's atmosphere is an enigma. Ever since its discovery, astronomers have been trying to explain how such a dense atmosphere and surface liquid arose and were preserved for millions of years. "Because Titan is the only moon in our Solar System with a substantial atmosphere, scientists have wondered for a long time what its source was," says Dr Kelly Miller, a research scientist at Southwest Research Institute in San Antonio, Texas, United States. "The main theory has been that ammonia ice from comets was converted, by impacts or photochemistry, into nitrogen to form Titan's atmosphere. While that may still be an important process, it neglects the effects of what we now know is a very substantial portion of comets: complex organic material."

But how is it replenished? Well, Miller believes this can be explained by 'cooking' organic materials brought to Titan via comets or other primitive objects during the moon's conception. When these materials are cooked, gases are released, and this is what is maintaining the levels of methane on Titan.



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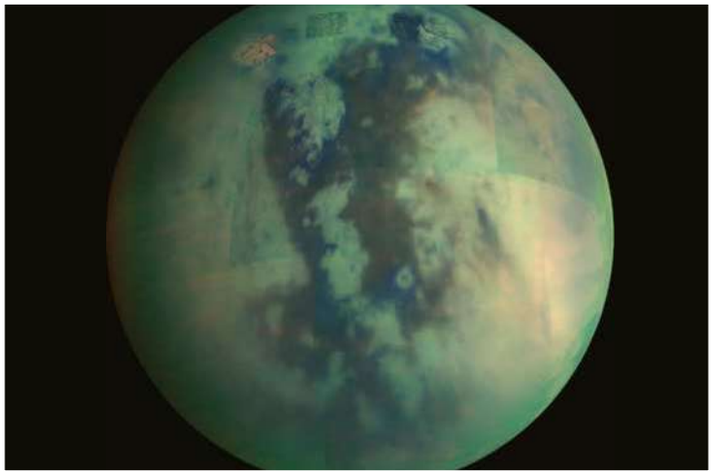


© NASA

CHANGING SEASONS

Much like seeing the seasons change from summer to winter on Earth, scientists have spotted signs of the changing seasons on Titan using valuable data from NASA's now-deceased Cassini spacecraft. Using pictures of the moon's northern hemisphere, Rajani Dhingra – a doctoral student in physics at the University of Idaho in Moscow, United States – and her team have seen rainfall on the north pole. The rainfall also provides the first indication of the beginning of a summer season.

"The whole Titan community has been looking forward to seeing clouds and rains on Titan's north pole, indicating the start of the northern summer, but despite what the climate models had predicted, we weren't even seeing any clouds," said Rajani Dhingra. "People called it the curious case of missing clouds."

Now that these images have been acquired and analysed, the case of Titan's seasons has become a little bit clearer, courtesy of Cassini and its Visual and Infrared Mapping Spectrometer instrument. The spacecraft's near-infrared capabilities allow it to peer inside the atmosphere and observe this rainfall. Compared to Earth's yearly cycle of four seasons, a season on Titan lasts seven Earth years.

DUST STORMS SWEEPING THE SURFACE

If you didn't already think that Titan was a harsh enough environment, Cassini also spotted giant dust storms sweeping across the moon's surface. This observation raises intrigue as astronomers try to work out what is generating this powerful gust around the equatorial region.

"Titan is a very active moon," says Sébastien Rodriguez, an astronomer at the Université Paris Diderot, France. "We already know that about its geology and exotic hydrocarbon cycle. Now we can add another analogy with Earth and Mars: the active dust cycle in which organic dust can be raised from large dune fields around Titan's equator."

In the same way the weather changes with the seasons on Earth, the same occurs on Titan. In this case, when the Sun crosses Titan's equator, massive clouds are formed in these tropical regions, creating powerful methane storms. This is what astronomers looking at this feature thought was occurring, but it turned out to be something completely different. After more modelling scientists discovered that these are actually clouds of organic molecules raised from the dune, and therefore the first observation of a dust storm on Titan.

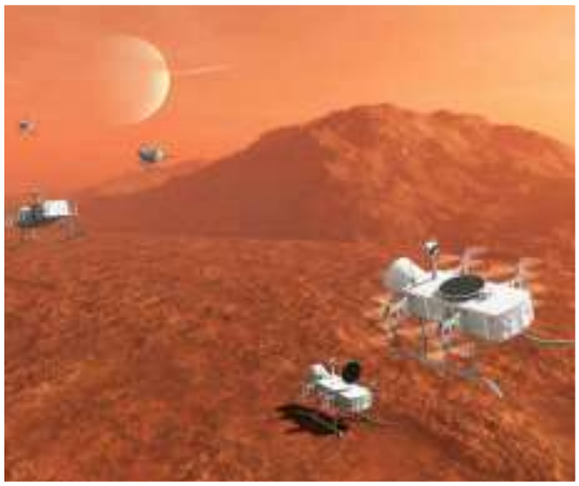
x3 images © NASA/JPL-Caltech

MISSION TO TITAN

Titan isn't exactly a nearby neighbour we can pop to and see how it's doing, like Mars. When Earth and Saturn are closest to each other they are still 1.2 billion kilometres (746 million miles) apart. This means visits to Titan in the past have been few and far between. The first probe to visit the Saturnian system was NASA's Pioneer 11 in 1979, followed by Voyager 1 and Voyager 2 in 1980 and 1981 respectively. NASA's Voyager spacecraft were pivotal in making initial measurements of its physical properties such as mass, density, composition and so on. These observations caught the attention of many because of their irregularity.

The best spy sent to the Saturnian system, and in particular Titan, was the Cassini spacecraft and its accompanying Huygens lander, a collaborative mission between NASA, the ESA and ASI. Cassini-Huygens arrived at Saturn in July 2004 and made many observations of the moon before Huygens was released with the intention to burst through the hazy atmosphere of Titan and land on its surface. On 14 January 2005, Huygens made its successful descent onto Titan before its batteries died and communication ceased with Cassini. All observations of Titan after the fact were made by Cassini before it ended its mission by crashing into Saturn's atmosphere in September 2017. The data collected by Cassini is still providing new discoveries over a year after the mission's end.

There have been talks of sending more probes to the exciting moon using new and innovative ways. One idea that is in advanced discussion is the 'Dragonfly' lander, as part of NASA's New Frontiers program. The Dragonfly lander will not just sit on the surface like Huygens, it will be a dual-quadcopter drone capable of moving around Titan's thick and nitrogen-rich atmosphere. This would allow astronomers to get a closer look at different surface features and would allow more freedom in movement than a rover.



LEFT: NASA's Dragonfly probe will revolutionise planetary exploration

HUYGENS' DESCENT TO TITAN

- **Time*:** 14 January 2005 10:13am UTC (11:13am CET)
  Activity: Huygens reaches the top of Titan's atmosphere.
- **Time:** 10:17am UTC (11:17am CET)
  Activity: Pilot parachute deploys, and a minute later the front shield is released and transmission to Cassini begins.
- **Time:** 10:32am (11:32am CET)
  Activity: Main parachute separates and drogue parachute deploys to guide Huygens to the right spot.
- **Time:** 11:57am UTC (12:57pm CET)
  Activity: The Gas Chromatograph Mass Spectrometer begins sampling the atmosphere before it touches the ground.
- **Time:** 12:34pm UTC (1:34pm CET)
  Activity: Huygens makes a successful touchdown on the surface of Titan.
- **Time:** 2:44pm UTC (3:44pm CET)
  Activity: Cassini stops collecting Huygens data, thus concluding its work, and at 3:14pm UTC the first data is sent to Earth.

*All times above are Earth Received Time - i.e. 67 minutes after the event has happened at the spacecraft

TITAN'S FACTS AND STATS

600 KM

Titan's atmosphere extends about 600 kilometres (370 miles) above its surface

Data suggests there could be the presence of a liquid ocean beneath the surface

The conditions on Titan could become more hospitable when the temperature of the Sun increases 6 billion years from now

ESA's Huygens holds the record for most distant landing of a human-made probe

Titan is tidally locked to Saturn, much like the Moon is to Earth, meaning only one side of Titan is facing Saturn at all times

The 'sand' on Titan's dunes is composed of dark hydrocarbon grains that resemble coffee grounds

2%

Jupiter's Ganymede is only two per cent larger, meaning there isn't much size between the two largest moons in the Solar System

PLANET PROFILE

URANUS

THE ICE GIANT THAT'S SHROUDED IN MYSTERY HAS FASCINATED EXPLORERS FOR DECADES

The seventh planet from the Sun, Uranus became the first planet to be found with the aid of a telescope on 13 March 1781 by British astronomer William Herschel. On that fateful night, he described observing a "nebulous star or perhaps a comet". Little did he know that he had just discovered Uranus, which was named after the Greek god of the sky – a name proposed by Johann Elert Bode in 1783.

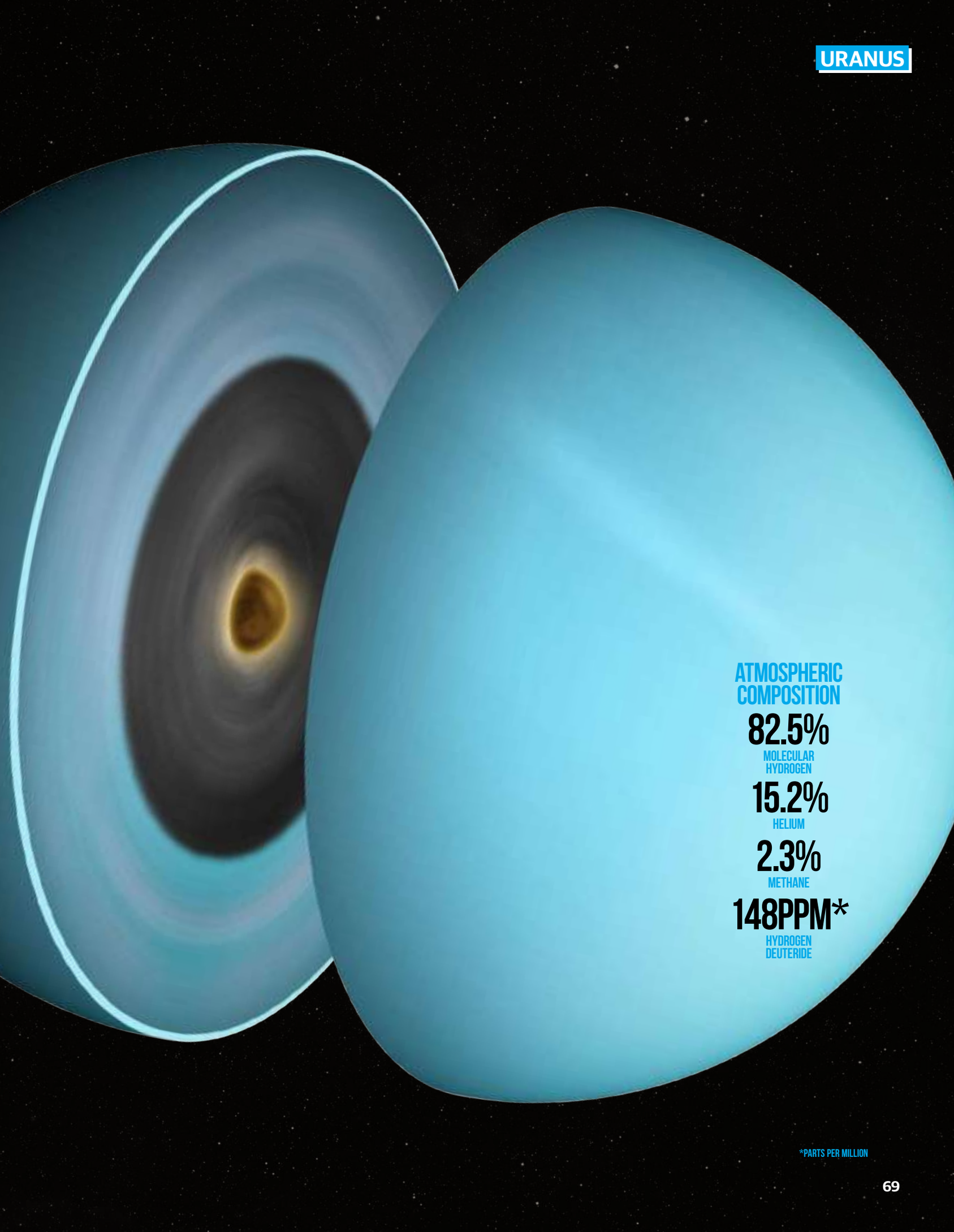
240 years later, Uranus remains a puzzle. What is known is that Uranus is located about 2.9 billion kilometres (1.8 billion miles) from the Sun, about 19 times the distance from Earth to the star, meaning that one orbit of the Sun takes 84 Earth years. The planet is enormous, with a diameter of 50,724 kilometres (31,518 miles) – four times wider than Earth. Uranus has a compositional mass that is 80 per cent a fluid mixture of water, ammonia (NH_3) and methane (CH_4) ices. It's the methane in the outer atmosphere that gives it its blue-green colour, but the thick cloud coverage does not allow our instruments to peer down any further, and is one reason why Uranus remains an enigma.

Astronomers strongly suggest that below the planet's cloud tops is a main atmosphere which contains mostly hydrogen and helium by composition and has traces of methane and other volatiles. Below that is the fluid icy mantle, which makes up most of its composition by mass, but it's also theorised that the pressure and temperatures here are enough to make it 'rain' diamonds at that depth. Finally, at the centre is the silicate iron-nickel core, thought to be between half to just over three times the mass of Earth.

Although there has only been one mission to visit the ice giant close up – Voyager 2 in 1986 – the planet has long been studied by ground and space-based telescopes, such as Hubble and the Keck Observatory in Hawaii. Observations throughout the years have revealed subtle yet surprising details about the pale planet. These include the planet's thin rings, which confirmed that Saturn is not an outlier and that rings can form around any planet. Astronomers have also been able to deduce that Uranus' planetary rotational tilt is off by a notable 97.77 degrees, which implies there was a collision in its early age that knocked it over.

Similar to the larger gas giants, Jupiter and Saturn, storms have been observed brewing in the cloud tops of Uranus. In November 2014, the planet was extremely active; storms raged on Uranus that were even observed by amateur astronomers. These observations caused another dilemma in regards to Uranus. As there seems to be no internal heat source and it's a huge distance from the Sun, astronomers question what's going on inside Uranus to make such storms arise. "The colours and morphology of this cloud complex suggest that the storm may be tied to a vortex in the deeper atmosphere similar to two large cloud complexes seen during the equinox," posits Larry Sromovsky, a planetary scientist at the University of Wisconsin-Madison, at the time of the storms' discovery.

"OBSERVATIONS THROUGHOUT THE YEARS HAVE REVEALED SUBTLE YET SURPRISING DETAILS ABOUT THE PLANET"



ATMOSPHERIC COMPOSITION

82.5%
MOLECULAR HYDROGEN

15.2%
HELIUM

2.3%
METHANE

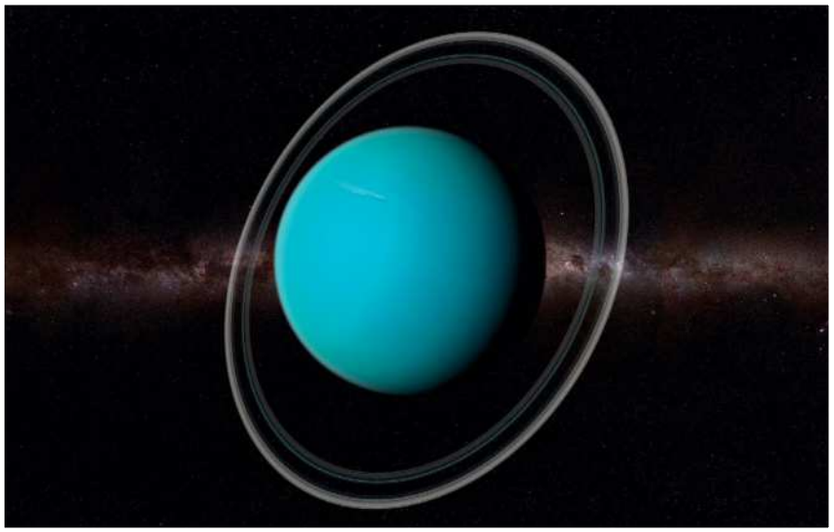
148PPM*
HYDROGEN DEUTERIDE

*PARTS PER MILLION

NEWS FROM URANUS

KNOCKING URANUS ABOUT

Astronomers at Durham University have completed multiple simulations focused on collisions with Uranus, stating that certain characteristics can be explained by an ancient, calamitous collision that took place roughly 4 billion years ago with an object twice the size of Earth. "We ran more than 50 different impact scenarios using a high-powered supercomputer to see if we could recreate the conditions that shaped the planet's evolution," says Jacob Kegerreis of Durham University's Institute for Computational Cosmology. "Our findings confirm that the most likely outcome was that the young Uranus was involved in a cataclysmic collision with an object twice the mass of Earth, if not larger, knocking it on its side and setting in process the events that helped create the planet we see today." Not only did this collision knock Uranus on its side, but the mystery impactor left a layer of insulating debris that keeps in the internal heat of Uranus. Insulating the ice giant, it would explain why we observe freezing temperatures of -216 degrees Celsius (-357 degrees Fahrenheit) in the planet's outer atmosphere.



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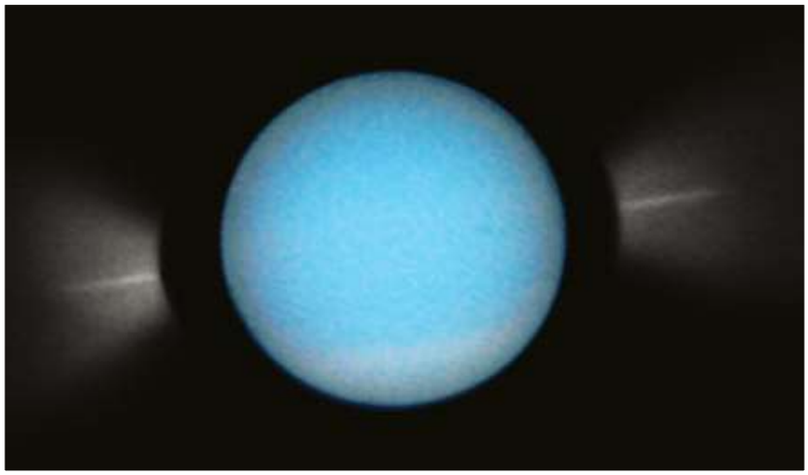

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URANUS' UNSETTLED MAGNETOSPHERE

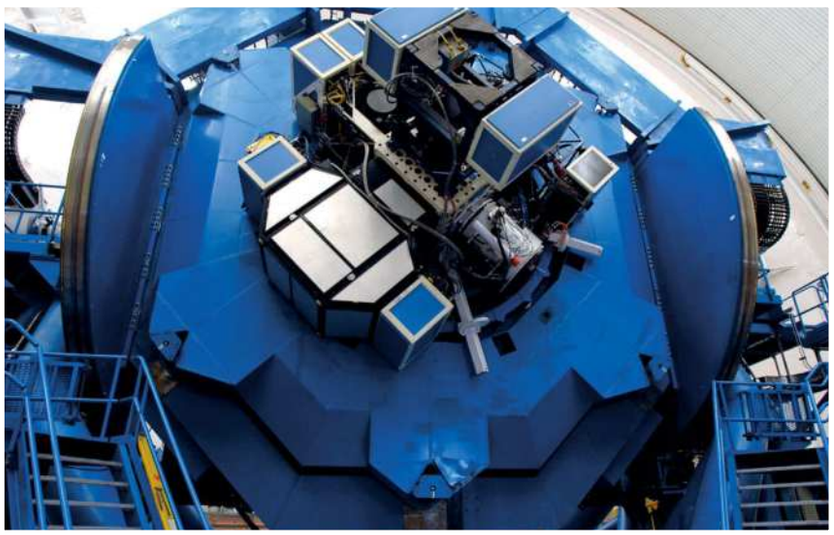
It's been 36 years since Voyager 2's flyby of Uranus, but its data is still fuelling more discoveries. Researchers from the Georgia Institute of Technology used Voyager data to reveal that Uranus' magnetosphere, the region encompassing the planet powered by its magnetic field, turns on and off like a light switch every day as it rotates around the planet. When the magnetosphere is 'open', solar wind is allowed to flow into it; if it's 'closed' it's essentially a shield that guards against the solar wind and deflects it away.

"Uranus is a geometric nightmare," says Carol Paty. "The magnetic field tumbles very fast. When the magnetised solar wind meets this tumbling field in the right way it can reconnect, and Uranus' magnetosphere goes from open to closed to open on a daily basis." The fact that Uranus rotates on its side and its magnetic field is off-centre and tilted by 60 degrees from its axis cause the magnetic field to fall asymmetrically relative to the solar wind direction.

URANUS SMELLS LIKE ROTTEN EGGS

Observations from the Gemini North telescope, located on Hawaii's Mauna Kea summit, revealed that hydrogen sulphide resides in the clouds of Uranus. This gas is what gives rotten eggs their distinctive smell, and it has been found to be one of the key ingredients that make up the clouds. This result came from dissecting the infrared light using Gemini's Near-Infrared Integral Field Spectrometer (NIFS) to reveal the spectral signature of different molecules. "This work is a strikingly innovative use of an instrument originally designed to study the explosive environments around huge black holes at the centres of distant galaxies," says Christopher J. Davis of the United States' National Science Foundation, a leading funder of the Gemini telescope. "To use NIFS to solve a long-standing mystery in our own Solar System is a powerful extension of its use."

By confirming the presence of this smelly gas, it confirms that there are distinct differences between the ice giants, Uranus and Neptune, as well as the other two gas giants, Jupiter and Saturn.



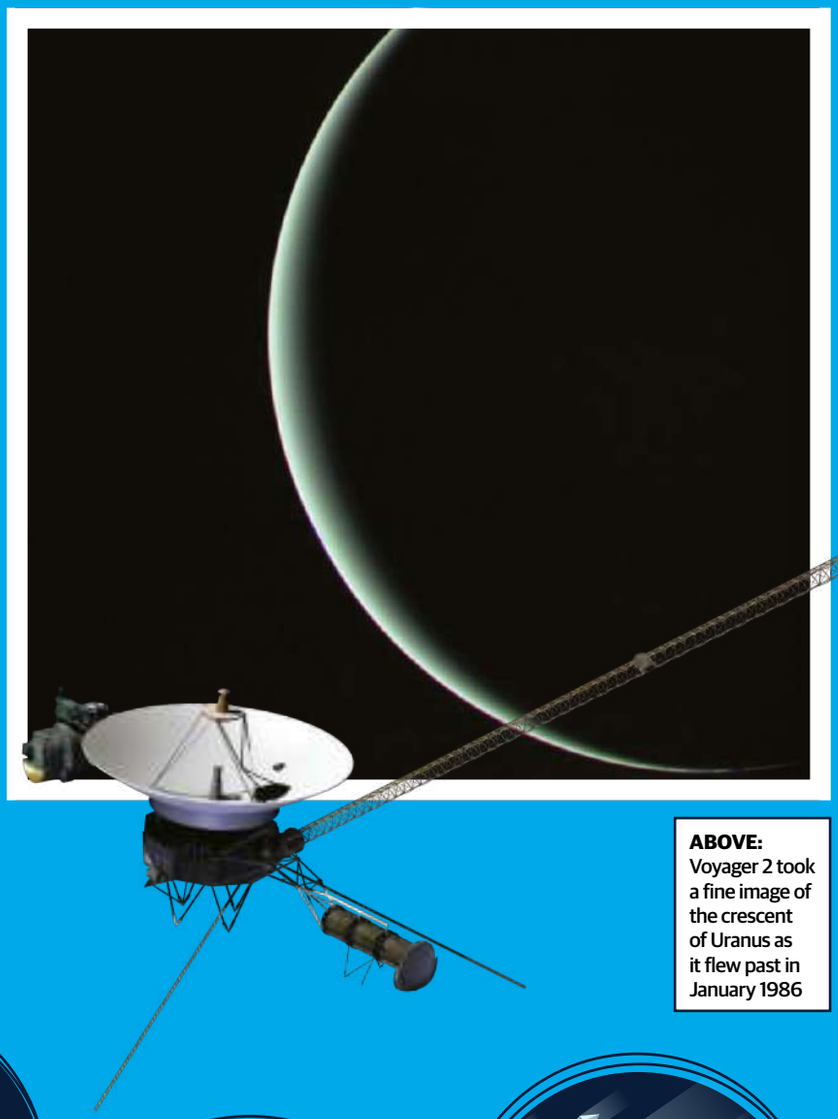
© Gemini

EXPLORATION OF AN ICE GIANT

Uranus is a relatively secluded planet, with a grand total of one spacecraft having visited it in the past. This lone ranger, NASA's Voyager 2 interplanetary probe, flew past the distant ice giant Uranus in 1986 while on its way out of the Solar System. Voyager 2 was able to get within 81,500 kilometres (50,642 miles) of the cloud tops, and its suite of instruments got to work. This flyby provided valuable data of the planet's atmosphere, rings, moons and magnetic field. This included the discovery of 11 new moons, two new rings and revealed that the planet's rotation rate is 17 hours and 14 minutes per rotation.

Although no spacecraft is currently exploring Uranus up close, there are preliminary plans in place to head to both Uranus and Neptune. NASA's Pre-Decadal Survey Mission Study outlines why Uranus and Neptune should be two of the next targets of exploration and contains a variety of potential orbiters, with a probe that could dive into Uranus' atmosphere. There could also be an orbiter carrying a payload between 50 and 150 kilograms for flybys of Uranus' major satellites. There would also be a narrow-angle camera that would be able to image Uranus and its 27 known moons, and possibly discover more.

"We do not know how these planets formed and why they and their moons look the way they do," says Amy Simon of NASA's Goddard Space Flight Center in Greenbelt, Maryland. "There are fundamental clues as to how our Solar System formed and evolved that can only be found by a detailed study of one, or preferably both, of these planets." Not only could these answers help us understand the evolution of our Solar System, but the knowledge could be applied to exoplanets around the galaxy, as ice giants seem to be extremely common within the Milky Way.



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ABOVE: Voyager 2 took a fine image of the crescent of Uranus as it flew past in January 1986

URANUS FACTS

17
A day on Uranus is 17 hours long, and the planet rotates backwards compared to Earth

Along with Neptune, Uranus is commonly referred to as an 'ice giant', as opposed to a 'gas giant', due to its icy mantle

27
Uranus has 27 known moons, all of which are named after characters from the works of William Shakespeare and Alexander Pope

In Uranus' mantle, the pressure and temperatures are ideal for creating nanosized diamonds, making it theoretically possible for it to 'rain diamonds'

<15x
The winds at Uranus can reach supersonic speeds, creating jet streams which are 10 to 15 times more powerful than anything seen on Earth

90°
Uranus rotates at a nearly 90-degree angle, thought to have been caused by a massive object roughly twice the size of Earth striking it

-218
Uranus is the coldest planet in the Solar System, with a lowest recorded temperature of -218 degrees Celsius (-370 degrees Fahrenheit)

13
Uranus has 13 known rings around it. The inner rings are narrow and dark, while the outer rings are brightly coloured

PLANET PROFILE
NEPTUNE

THE ISOLATED AZURE GIANT REMAINS A RELATIVE MYSTERY

Neptune is the eighth planet from the Sun. It was the first planet to have its existence predicted by mathematical calculations before it was seen through a telescope on 23 September 1846. Irregularities in the orbit of Uranus led French astronomer Alexis Bouvard to suggest that the gravitational pull from another celestial body might be responsible. German astronomer Johann Galle then relied on subsequent calculations to help spot Neptune via telescope. Previously, Galileo Galilei sketched the planet but he mistook it for a star due to its slow motion. In accordance with all the other planets seen in the sky, this new world was given a name from Greek and Roman mythology: Neptune, after the Roman god of the sea.

Only one mission has flown by Neptune– Voyager 2 in August 1989 – meaning that astronomers have done most studies using ground-based telescopes. Today, there are still many mysteries about the cool, blue planet, such as why its winds are so speedy and why its magnetic field is offset. While Neptune is of interest because it is in our own Solar System, astronomers are also interested in learning more about the planet to assist with exoplanet studies. Specifically, some astronomers are interested in learning about the habitability of worlds that are somewhat bigger than Earth.

Those that are closer to Earth's size are called 'super-Earths', while those that are closer to Neptune's size are 'mini-Neptunes'. However, there's some debate about those terms given that today's telescope technology doesn't make it possible to view how much atmosphere is on those planet types, making it difficult to make a distinction. Like Earth, Neptune has a rocky core, but it has a much thicker atmosphere that prohibits the existence of life as we know it. Astronomers are still trying to figure out at what point a planet becomes so large that it may pick up a lot of gas from the area, making it difficult or impossible for life to exist.

Neptune's cloud cover has a vivid blue tint that is partly due to an as-yet-unidentified compound and the result of the absorption of red light by methane in the planet's mostly hydrogen-helium atmosphere. Photos of Neptune reveal a blue planet, and it's often dubbed an ice giant, since it possesses a thick, slushy fluid mix of water, ammonia and methane ices under its atmosphere. It is roughly 17 times Earth's mass and nearly 58 times its volume. Neptune's rocky core alone is thought to be roughly equal to Earth's mass.

Despite its great distance from the Sun, which means it gets little sunlight to help warm and drive its atmosphere, Neptune's winds can reach up to 2,400 kilometres (1,500 miles) per hour – the fastest detected yet in the Solar System. These winds were linked with a large, dark storm that Voyager 2 tracked in Neptune's southern hemisphere in 1989. This oval-shaped, counterclockwise-spinning 'Great Dark Spot' was large enough to contain the entire Earth, and moved westward at nearly 1,200 kilometres (750 miles) per hour. This storm seemed to have vanished when the Hubble Space Telescope later searched for it. Hubble has also revealed the appearance and then fading of other dark spots over the past decade, and a new one was observed in 2016. It doesn't look like Neptune is finished with surprising scientists just yet.

LEFT: A Voyager 2 view of Neptune

"TODAY THERE ARE STILL MANY MYSTERIES ABOUT THE COOL, BLUE PLANET, SUCH AS WHY ITS WINDS ARE SO SPEEDY"

ATMOSPHERIC COMPOSITION

80%
HYDROGEN

19%
HELIUM

1.5%
METHANE

OVERALL COMPOSITION

25%
ROCK

60-70%
ICE

5-15%
HYDROGEN AND HELIUM

NEWS FROM NEPTUNE

A DARK STORM ON NEPTUNE MYSTERIOUSLY REVERSED

A dark storm on Neptune abruptly switched direction and started moving away from almost certain death, puzzling astronomers. NASA's Hubble Space Telescope first spotted the vortex in 2018. A year later, the storm began drifting southward towards Neptune's equator, following the path of several storms before it. Usually these dark spots on Neptune live for a few years before either vanishing or fading away. However, the storm mysteriously stopped moving south and made a sharp U-turn, drifting back northwards. At the same time, astronomers spotted a second, smaller dark spot on the planet. They theorise that this smaller 'cousin' may be a piece of the original vortex that broke off and drifted away.

Although Hubble has tracked similar storms on Neptune over the past 30 years, astronomers have never seen such unpredictable atmospheric behaviour. The 2018 storm, which was 7,403 kilometres (4,600 miles) across, is the fourth-darkest spot Hubble has tracked since 1993.

NEPTUNE'S SMALLEST MOON HAS A VIOLENT PAST

Hippocamp is believed to have a diameter of about 34 kilometres (21 miles). The tiny moon circles in the same general neighbourhood as six moons discovered by Voyager 2 during the probe's flyby of Neptune in 1989. Hippocamp is just 12,000 kilometres (7,450 miles) inland to the largest and outermost of these other six, Proteus.

Like Earth's Moon, Proteus has been slowly spiralling away from its parent planet. So has Hippocamp, though at a much slower rate. About 4 billion years ago, Proteus was probably right next to Hippocamp and would have gobbled the smaller moon up. Scientists believe that Hippocamp was once part of its larger neighbour and likely coalesced from pieces of Proteus that were blasted into space by a long-ago comet impact.

NEPTUNE'S MOON TRITON HAS A RARE KIND OF ICE

Neptune's largest moon Triton boasts an uncommon icy mixture of carbon monoxide and nitrogen, which could help astronomers better understand the conditions of other distant alien worlds.

Using the Gemini Observatory in Chile and a high-resolution spectrograph called the Immersion Grating Infrared Spectrometer (IGRINS), a visiting instrument for Gemini, astronomers detected a distinct infrared signature on Triton, revealing a mixture of carbon monoxide and nitrogen frozen as solid ice. This finding helps explain seasonal atmospheric changes on Triton and how material is transported across the moon's surface via geysers.

The icy mixture detected on Triton could help explain the moon's iconic geysers, which are the dark, windblown streaks first observed by NASA's Voyager 2 spacecraft in the moon's south polar region. These distinct streaks are believed to be erupted material from an internal ocean, or an icy mixture that migrates around the surface in response to changing seasonal patterns of sunlight.

WHEN TRITON CRASHED THE PARTY AT NEPTUNE

Neptune's original satellites may have been destroyed when its largest moon, Triton, entered the picture. The massive moon may have tossed some of the original satellites into the ice giant, kicked others out of orbit and swallowed up the rest, creating a new family that doesn't look much like those of other giant planets.

For years scientists have suspected that Triton wasn't part of Neptune's original collection of moons. The massive moon has a backward orbit and makes up over 99 per cent of all the mass orbiting the planet. They think it's a captured object whose orbit was circularised by debris discs created by impacts.

The moons of Jupiter, Saturn and Uranus are all well-behaved compared with Neptune's. The other three gas giants have a wealth of satellites – Jupiter has 79 to Neptune's 14 – travelling in nearly circular paths around their equators. While Triton's path is circular, it travels backwards compared with Neptune's rotation, and spins backwards too.

© NASA

EVOLUTION OF NEPTUNE

- **Date:** 23 September 1846
  Activity: Astronomer Johann Gottfried Galle viewed Neptune through a telescope for the first time
- **Date:** 10 October 1846
  Activity: Neptune's largest moon Triton was discovered
- **Date:** 25 August 1989
  Activity: NASA's Voyager 2 flew by Neptune and came within just 3,000 kilometres (1,860 miles) of the planet's north pole
- **Date:** 1 July 2013
  Activity: Neptune's smallest moon S/2004 N1 was discovered during an analysis of older Hubble images
- **Date:** 8 October 2013
  Activity: Neptune's 'lost' moon Naiad was spotted for the first time in 20 years. The tiny moon had remained unseen since the cameras on NASA's Voyager 2 spacecraft first discovered it in 1989

NEPTUNE BY NUMBERS

165
EARTH YEARS
How long Neptune takes to complete an orbit of the Sun

-214°C
Average temperature on Neptune

14
The number of known moons of Neptune

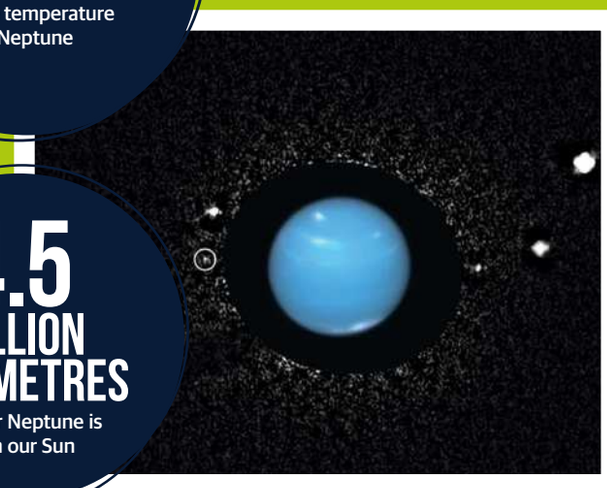
28.3°
The angle of Neptune's tilt as it orbits the Sun

4.5
BILLION KILOMETRES
How far Neptune is from our Sun

7.6
BILLION SQUARE KILOMETRES
The surface area of Neptune

27x
How many times more powerful Neptune's magnetic field is than Earth's

16
HOURS
The length of a day on Neptune



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"SCIENTISTS SUSPECTED TRITON WASN'T PART OF NEPTUNE'S ORIGINAL COLLECTION OF MOONS"

DWARF PLANET PROFILE

PLUTO

THE DWARF PLANET IN THE REALMS OF THE KUIPER BELT IS NOT JUST A BARREN BALL OF ROCK AND ICE

Pluto is arguably the most famous of all the dwarf planets, with many still fighting in its corner to get back its status as a planet. It resides in the darkest depths of the Solar System, the Kuiper Belt, 5.9 billion kilometres (3.7 billion miles) away from the Sun, which is roughly 40 times the Earth-Sun distance. The former member of the nine planets of the Solar System was discovered in 1930 by an American astronomer by the name of Clyde Tombaugh. Although Tombaugh discovered the dwarf planet, the credit for naming Pluto goes to an 11-year-old girl from Oxford, England, called Venetia Burney. She suggested that the then-planet be named after the Roman god of the underworld, which can't be far off the same conditions as the Kuiper Belt – dark, lonely and unbearably cold, with temperatures reaching as low as -240 degrees Celsius (-400 degrees Fahrenheit).

Its enormous distance from the Sun leads to Pluto having an equally enormous year – it takes 248 Earth years to complete one orbit. To put that into context, if Pluto completed an orbit this year, then when it started that orbit, no one would have had a clue about Pluto, and French astronomer Charles Messier would have still been in the process of constructing the famous Messier Catalogue of deep-sky objects.

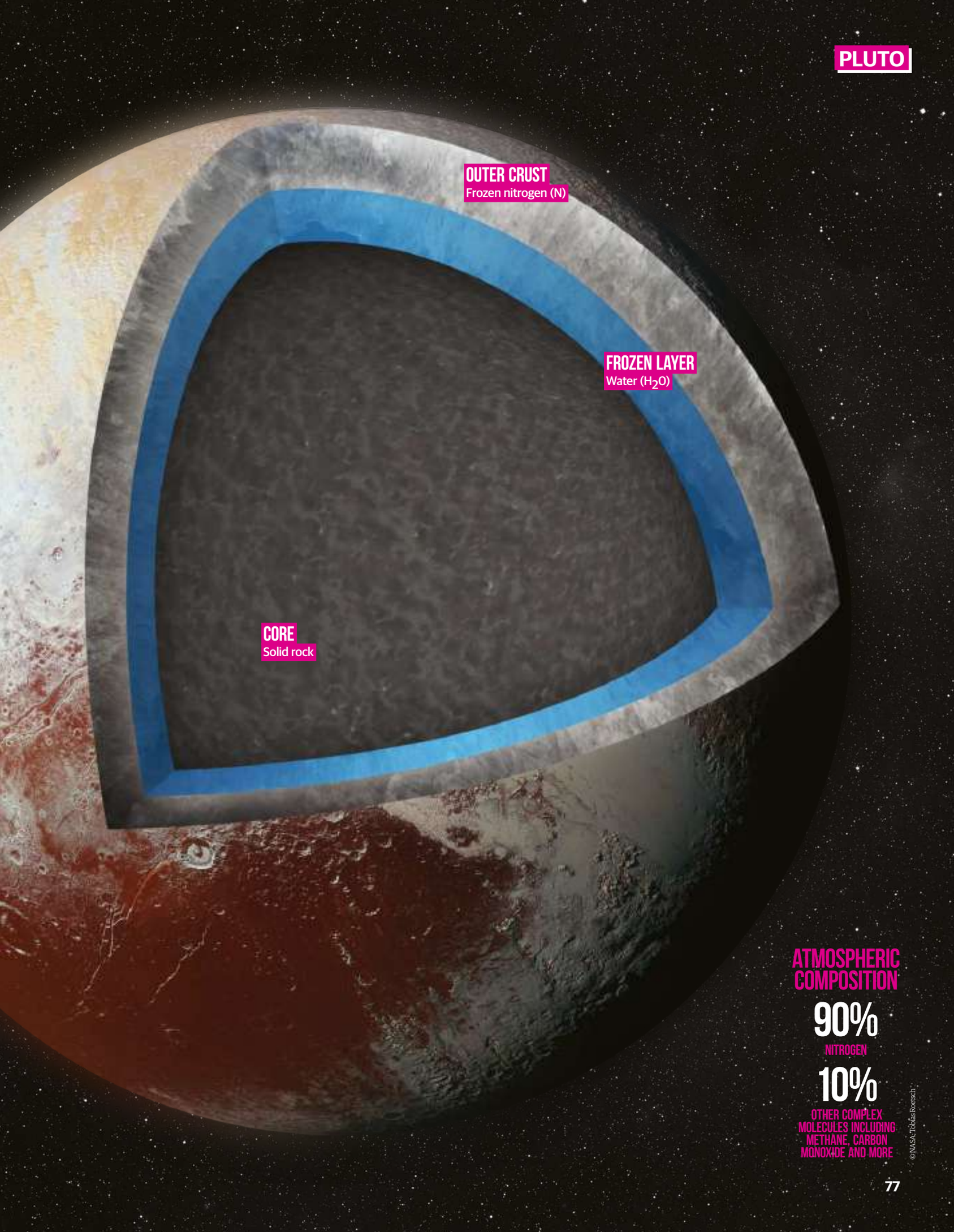
Pluto saw its declassification to a dwarf planet in 2006 when the International Astronomical Union defined the criteria of a planet, with Pluto just falling short. It is only a small world: it is roughly 2,400 kilometres (1,500 miles) wide, making it about two-thirds the size of the Moon and half the width of the United States. Although Pluto had been observed by many ground-based telescopes, and even NASA/ESA's Hubble Space Telescope, its true form and physical characteristics weren't apparent until it had its one-and-only flyby by NASA's New Horizons spacecraft, launched in 2006.

After the flyby in 2015, the surface of Pluto came into marvellous resolution, and many people of Earth marvelled at its beauty. "The complexity of the Pluto system – from its geology to its satellite system to its atmosphere – has been beyond our wildest imagination," says Alan Stern, New Horizons principal investigator from the Southwest Research Institute in Boulder, Colorado, USA. "Everywhere we turn are new mysteries."

When astronomers first observed the surface they noticed a host of mountains, valleys, plains and craters, but the plains of frozen nitrogen gas exhibit very few craters, meaning that there must be some sort of surface replenishment – possibly material spraying from a subsurface ocean. All of this was possible to see with Pluto's virtually nonexistent atmosphere that consists of molecular nitrogen, with traces of methane and carbon monoxide also having been detected.

Pluto has five known moons: Charon, Nix, Hydra, Kerberos and Styx. These moons were likely formed as the result of a collision between Pluto and an object of similar size billions of years ago. Charon is the largest of these moons and is about half the size of Pluto, making it the largest moon relative to its host. In fact, the Pluto-Charon double act can sometimes be referred to as a double planet system.

LEFT: Pluto and its main moon Charon compared against Earth



ATMOSPHERIC COMPOSITION

90%
NITROGEN

10%
OTHER COMPLEX MOLECULES INCLUDING METHANE, CARBON MONOXIDE AND MORE

NEWS FROM PLUTO

WARMING THE HEART OF PLUTO

When New Horizons flew past Pluto in 2015, it shattered perceptions of a dull, rocky ball and instead opened astronomers' eyes to the idea this could be an active world. On its flyby the spacecraft revealed a heart-shaped region in the northern hemisphere of the dwarf planet known as Tombaugh Regio. After studying data on this region, astronomers have found evidence for a subsurface ocean existing under the layer of nitrogen ice.

"This could mean there are more oceans in the universe than previously thought, making the existence of extraterrestrial life more plausible," says Shunichi Kamata of Hokkaido University in Japan. This study suggests that there is a layer of gas hydrates – ice-like solids composed of gases trapped in molecular water – that insulates that region of Pluto, which prevents freezing within its interior. Ocean worlds are an exciting area of research in the Solar System because it means that one of the fundamental needs for life is abundant beyond our home planet. It could mean that extraterrestrial life could exist elsewhere in the Solar System.

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RE-OPENING THE PLANETARY DISCUSSION

29 April 2019 saw an informal vote about whether Pluto should be reinstated as a planet or remain a dwarf planet. This vote saw the inclusion of experts on the matter, including NASA's New Horizons principal investigator Alan Stern and the former president of the International Astronomical Union (IAU) Ron Ekers.

It was the IAU that stripped Pluto of its planetary status in 2006. One of the main criteria that denotes a planet was it having "cleared the neighbourhood around its orbit", but as Pluto crosses the orbit of Neptune it did not meet this requirement. This decision was made after a long-winded process of deciding what should define a planet by the IAU, but sadly Pluto did not reach said criteria, argued Ekers.

When Stern took to the stage, he argued that Pluto is much more of a world – with oceans, mountains and glaciers just to name some features – and that it is much harder to clear an orbit in the region beyond Neptune than it is closer to the Sun. After the debate a vote was taken; 30 people voted in favour of keeping Pluto as a dwarf planet, whereas a whopping 130 voted in favour of Pluto being a planet.

AMMONIA MAKES PLUTO LOOK YOUNGER

Ammonia – a nitrogen atom with three hydrogen atoms branching off – is a building block of life and a welcome sight to astronomers. As ammonia is a key compound for life as we know it, when it is seen on other planets or other bodies, it ticks an important box when looking for what makes a world habitable. Obviously Pluto has many things going against it in terms of habitability – its tiny size, its huge distance from the Sun, relatively no atmosphere and so on – but ammonia is enough to gain the attention of many astrobiologists.

This compound, however, is short-lived on such an exposed body. In the words of Cristina Dalle Ore, a planetary scientist at NASA's Ames Research Center in Moffett Field, California, United States, ammonia "is a fragile molecule and gets destroyed by ultraviolet irradiation as well as cosmic rays. Therefore, when found on a surface it implies that it had been emplaced there relatively recently, some million years before."

Therefore there must be some form of geological activity depositing ammonia onto the surface. Whether there is recent volcanic activity, active vents or whatever gateway there may be between the surface and the potential subsurface ocean, astronomers are now determined to find out how ammonia is getting to the surface to make Pluto look younger.

© NASA

EXPLORING THE PAST AND FUTURE OF PLUTO

Due to the enormous distance to Pluto, exploration has been minimal. For a long time, any observations relied on Earth-based telescopes, particularly Hubble, which produced the highest resolution maps of the dwarf planet in 2002 to 2003.

NASA, however, deemed this not quite good enough, choosing to send a space probe to Pluto and see what it was all about. New Horizons was the project chosen to do so and was launched on 19 January 2006, beginning its nine-year journey to Pluto. When it arrived in July of 2015, New Horizons flew as close as 12,500 kilometres (7,800 miles) to the planet and revealed an incredibly interesting surface. Upon closer inspection of the data, the New Horizons team found potential evidence of a subsurface ocean, not just water-ice frozen under the face of the dwarf planet. This could have amazing repercussions in understanding how water exists in the Solar System.

After the New Horizons flyby, planetary scientists have become more interested in Pluto and are desperate to learn as much about it as possible. This has laid down another challenge at NASA's feet which could soon be picked up by the aerospace engineering company Global Aerospace Corporation (GAC), who are interested in creating the 'Pluto Hopper'.

The idea behind this hopper is to drop a lander onto the surface of Pluto using an inflatable balloon to slow down the craft. One issue with this, however, is that Pluto has an incredibly thin atmosphere. It also has a low surface gravity – only six per cent of Earth's – and the spacecraft would have to slow down a lot as it arrives at high speeds. Although these are hard obstacles to overcome when trying to place a lander on the surface of the tiny dwarf planet, they are doable, and scientists and engineers are continuing to work out how to get back to Pluto one day.

© Adrian Mann;

BELOW The 'Pluto Hopper' is still in the designing phase of its mission

NEW HORIZONS AND PLUTO: A BRIEF ENCOUNTER

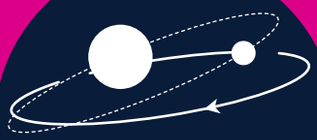
- **Date:** 19 January 2006
  Activity: New Horizons was launched on top of an Atlas V rocket from Cape Canaveral Air Force Station, Florida.
- **Date:** 28 February 2007
  Activity: The craft had a 'gravity assist' from Jupiter to gather more speed, which reduced its journey time by three years.
- **Date:** 28 June 2007
  Activity: New Horizons went into hibernation for the long journey ahead.
- **Date:** 6 December 2014
  Activity: Engineers woke New Horizons up ahead of its flyby to test equipment.
- **Date:** 15 May 2015
  Activity: New Horizons had officially imaged Pluto in a better resolution than the Hubble Space Telescope.
- **Date:** 14 July 2015
  Activity: The day of the flyby had arrived; a historic moment that returned unbelievable data about the dwarf planet.

PLUTO'S FACTS AND STATS

153

One day on Pluto takes 153 hours. It has a retrograde rotation, meaning it spins from east to west

NASA's New Horizons was the fastest man-made object launched from Earth at 16.26 kilometres (10.10 miles) per second



Charon, Pluto's largest moon, also takes 153 hours to complete one orbit around Pluto, meaning this moon never rises or sets

1/900

The Sun would be 1/900 the brightness on Pluto than it is on Earth, equal to 300-times the brightness of a full Moon

Pluto's mountains can reach as high as two to three kilometres (6,500 to 9,800 feet) and are essentially composed of water ice

There is no evidence to suggest Pluto has a magnetosphere, but its small size and slow rotation suggests it is unlikely

It takes 5.5 hours for sunlight to reach Pluto, as light has to travel 40 times as far than it does to Earth

MOON PROFILE

CHARON

THE SECRETS OF PLUTO'S LARGEST MOON

Nobody knew it was there until 1978. For almost 50 years after Pluto's discovery in 1930, the dwarf planet had no known companions out there on the edge of the Solar System. Today, of course, in the wake of the New Horizons mission and myriad discoveries since the first inklings of the Kuiper Belt came in 1992, we know it positively teems out there. Charon is one of a system of five moons, and Pluto is the largest member of a huge collection of objects orbiting beyond Neptune. The ongoing hunt for a large planet in the extreme reaches of the Solar System has so far come to nothing, and this is the domain of the small, with Pluto's reclassification as a dwarf planet just the first in a whole raft of triumphantly tiny accolades.

Pluto's largest moon, however, has some remarkable features of its own, despite only having a diameter of 1,212 kilometres (753 miles) – about 10.5 per cent that of Earth's. One-eighth the mass of its co-orbitee Pluto, and half the diameter, it's tidally locked to the larger body, but large enough that the two orbit a centre of mass between them. The International Astronomical Union's general assembly considered a proposal in 2006 to reclassify the pair as a double planet, but despite it being spherical, it wasn't clear Charon was in hydrostatic equilibrium, a state in which the force of gravity is balanced by outward pressure from the body. This state is necessary to give it dwarf planet status.

Charon's name, which it shares with the ferryman who takes souls over the River Styx to Hades in Greek mythology – pronounced with a hard 'K' sound at the beginning – where they're guarded by the three-headed dog Cerberus, comes from its discoverer James Christy, whose wife is named Charlene – he pronounces Charon with a 'sh' sound, as does the New Horizons team. But a 1940 novel by Edmond Hamilton, Calling Captain Future, names three Plutonian moons as Charon, Styx and Cerberus. Whatever the origin, the name was officially announced in January 1986, replacing the temporary designation S/1978 P 1. As more moons were discovered around Pluto, they were named Styx; Nix, the Greek goddess of the night; Kerberos – Cerberus was already taken by an asteroid – and Hydra, a mythological nine-headed water monster.

Charon orbits so close to Pluto that when examining photographic plates of the erstwhile planet, taken using the 1.55-metre (61-inch) telescope at United States Naval Observatory Flagstaff Station, all Christy saw was a bulge in the shape of the tiny disc. By revolving around the disc with time, it revealed itself to be a moon. It wasn't until the development of adaptive optics for Earth-based telescopes that it became possible to resolve the pair as separate discs. The bodies whip around each other once every 6.4 days at an average distance of 19,640 kilometres (12,203 miles), and take 248 years to orbit the Sun.

We had to wait until the New Horizons probe entered the system in 2015 to get a really good look at Charon. A largely grey world of rock and water ice with a reddish cap at its north pole, it remains a fascinating part of the Solar System with more secrets to be discovered.

RIGHT: Charon is half the size of its parent body, dwarf planet Pluto

CHARON

MOON COMPOSITION

55%
ROCK

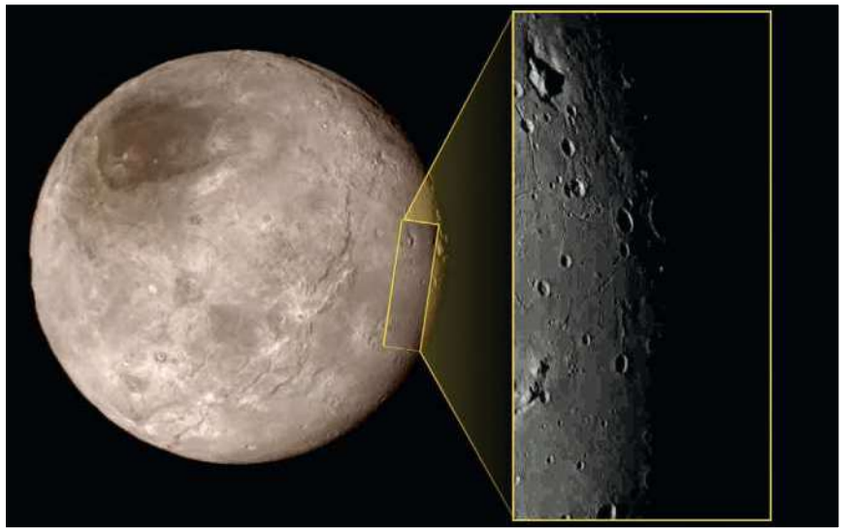
45%
ICE

"A FASCINATING PART OF THE SOLAR SYSTEM WITH MORE SECRETS TO BE DISCOVERED"

NEWS FROM CHARON

FANTASY FEATURES

Various features on the surface of Charon, imaged by the New Horizons probe, have been given official names by the International Astronomical Union Working Group for Planetary System Nomenclature. The names reflect travellers and explorers, especially those with mysterious destinations. Dorothy Crater, for example, is named after the protagonist from *The Wizard of Oz*, while Caleuche Chasma is named for the mythological ghost ship that travels the seas around the small island of Chiloé off the coast of Chile. Mandjet Chasma is named for one of the boats in Egyptian mythology that carried the Sun god Ra across the sky each day, and Nemo Crater honours the captain of the Nautilus, the submarine in Jules Verne's novels *Twenty Thousand Leagues Under the Sea* and *The Mysterious Island*. The New Horizons team had their own names for distinctive areas of the moon, including Oz Terra, Charon's only highland region, named after the land of Oz, and McCaffrey Dorsum, the moon's only ridge, named after science-fiction author Anne McCaffrey.



WHAT'S IN THE CAP?

Charon's north polar cap is a different colour to the rest of its surface, and there might be a fascinating explanation: Pluto may be sharing its atmosphere with its largest moon. A study from the Lowell Observatory in Arizona modelled conditions on Charon over the past few billion years and discovered that radiation had been stripping the hydrogen from frozen methane on the dwarf planet's surface. This left behind carbon, which joined with other molecules to make heavier materials more able to stick to the surface rather than be lost to space. These became organic molecules called tholins, which produce the red hue. There was speculation after New Horizons revealed Charon's red pole that the cap was enriched with tholins, which could have gotten there via atmosphere transfer. Pluto's gravity isn't high enough to hold onto its thin atmosphere, but Charon's is powerful enough to capture some of the lost gases. Charon's poles freeze the methane, but it evaporates in summer, leaving the heavier, redder molecules behind.

MAPS MADE

The New Horizons spacecraft did more than take photographs when it passed through the system in 2015. The wealth of data it sent back is still being analysed, years after the probe moved on to targets deeper in the Kuiper Belt. New Horizons only directly imaged 45 percent of the surface of Charon in daylight, meaning there are still secrets left to uncover for future missions, but by stitching together images from a pair of New Horizons' cameras, a team from the Universities Space Research Association's Lunar and Planetary Institute in Texas was able to create a height map of the surveyed areas. From this, the size of surface features could be calculated, including the six-kilometre (3.7-mile) high Tenzing Montes, the moon's highest mountains. This height also allows an insight into their composition – methane ice isn't strong enough to support peaks of that height, meaning they must be made of water ice, frozen harder than rock in the chilling temperatures of -250 degrees Celsius (-418 degrees Fahrenheit).

FUTURE EXPLORATION OF CHARON

New Horizons passed through the Pluto system without stopping, and is continuing to speed through the Kuiper Belt on its way out of the Solar System as one of the fastest human-made objects ever launched. Another probe could hypothetically spend much more time investigating Pluto and its moons, using Charon as a source of momentum.

The mission – which is purely theoretical at this point, having been demonstrated by New Horizons' software lead Tiffany Finley – could explore each of the moons in the Pluto system, passing each at least five times, returning to Charon after each one for a course-correcting gravity assist. Using an electric propulsion system similar to that on the Dawn mission to Vesta and Ceres, the tour would only use fuel for 'clean-up manoeuvres' designed to make sure it was going in exactly the right direction, making it an efficient way to visit the moons. The Cassini probe did something similar using Titan while touring the moons of Saturn.

The mission could even be extended so that with one final gravity assist the probe would enter the Kuiper Belt and enter orbit around a second dwarf planet. New Horizons' visit to Pluto was a big success, but it was necessarily limited by the speed at which it passed the system. A second probe spending more time in the area would potentially be able to answer many of the remaining questions about Pluto, Charon and its scattering of small moons.

© Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute.

BELOW: Artist's impression of the New Horizons probe flying by Pluto and Charon

THE EVOLUTION OF CHARON

- **Date:** 4.5 billion years ago
  Activity: Two Kuiper Belt objects collide and go into orbit around a shared barycentre.
- **Date:** 1930
  Activity: Discovery of Pluto by Clyde Tombaugh.
- **Date:** 1978
  Activity: Discovery of Charon by James Christy.
- **Date:** 1980s
  Activity: Pluto and Charon eclipse one another several times, allowing astronomers to study their spectra and work out their surface composition.
- **Date:** 1994
  Activity: Hubble images Pluto and Charon from 4.4 billion kilometres (2.7 billion miles) away.
- **Date:** 2007
  Activity: Observations by the Gemini Observatory suggest there are active cryogeysers on Charon's surface.
- **Date:** 2015
  Activity: New Horizons arrives in the system, gathers data and then leaves.
- **Date:** 2017
  Activity: NASA's Ames Research Center confirms Charon once had active plate tectonics like Earth.
- **Date:** 2019
  Activity: A geomorphological map of Charon's surface is published, dividing the surface into 16 types.

CHARON BY NUMBERS

19,640 KILOMETRES
The average distance between Charon and Pluto

40 KILOMETRES
Diameter of Kubrick Mons, a strange mountain in a moat on Charon

7.5 BILLION KILOMETRES
The distance from Earth to Pluto when they're on opposite sides of the Sun

-258°C
Winter temperature in Charon's north polar region

-213°C
Summer temperature in Charon's north polar region

14 KILOMETRES
The depth of Charon's Caleuche Chasma, roughly seven-times deeper than the Grand Canyon

SIX KILOMETRES
Height of Tenzing Montes, Charon's highest peaks

© NASA

DWARF PLANET PROFILE

MAKEMAKE

MAKEMAKE IS PARTLY RESPONSIBLE FOR PLUTO'S CONTROVERSIAL CHANGE IN PLANETARY STATUS

Makemake is a dwarf planet in the outer Solar System. It was the fourth body to be identified as a dwarf planet. Makemake is large and bright enough to be studied by a high-end amateur telescope. Makemake was first observed in March 2005 by a team of astronomers at the Palomar Observatory in California. Provisionally known as 2005 FY9, the tiny planetoid was nicknamed Easterbunny by the group. The team was also responsible for the discovery of dwarf planet Eris and involved in the controversial discovery of the dwarf planet Haumea. Makemake is named for the god of fertility in Rapa Nui mythology. The Rapa Nui live on Easter Island in the southeastern Pacific Ocean. Makemake was the chief god, the creator of humanity and the god of fertility.

Makemake is the second-brightest known object in the outer Solar System, just slightly dimmer than Pluto. At 1,400 kilometres (870 miles) wide, it's about two-thirds the size of the more well-known dwarf planet. It orbits beyond the range of Pluto, but closer to the Sun than Eris, taking approximately 305 Earth years to circle the Sun. Makemake is reddish-brown in colour, leading scientists to conclude that it contains a layer of methane at its surface, possibly in pellets. Signs of frozen ethane and frozen nitrogen have also been determined.

Astronomers took advantage of the dwarf planet's passage in front of a star – called an occultation – to determine that it lacks a significant atmosphere, a surprise given its similarities to Pluto, which has a thin one. The scientists also calculated how much light the planet reflected, a rate comparable to dirty snow. The planet is dimmer than Pluto but brighter than Eris.

Like all the known dwarf planets but Ceres, Makemake travels through the Kuiper Belt, the distant region of ice and rock that lies at the outer edges of our Solar System. It can travel as far out as 53 times the distance between Earth and the Sun and come as close as 38 times that same distance throughout its orbit. Makemake spins on its axis once every 22.5 hours, with a day just shorter than Earth's. Makemake's moon, designated S/2015 (136472) 1, but currently nicknamed MK 2, is about 160 kilometres (100 miles) in diameter. It lies about 20,900 kilometres (13,000 miles) from the surface of Makemake.

Makemake, along with Eris and Haumea, was responsible for Pluto's drop in status from planet to dwarf. Though Makemake and Haumea are just smaller than Pluto, Eris is more massive; Ceres, found in the asteroid belt, is the smallest of the bunch. In 2006, the International Astronomical Union (IAU) created a new category of bodies known as 'dwarf planets' and reclassified the definition of a planet. A planet circles the Sun but doesn't orbit anything else, is large enough to be rounded by its own gravity and has cleared its neighbourhood of orbiting bodies. Pluto failed to make the cut because it doesn't clear the debris in its orbital path.

> "MAKEMAKE IS THE SECOND-BRIGHTEST KNOWN OBJECT IN THE OUTER SOLAR SYSTEM, SLIGHTLY DIMMER THAN PLUTO"

ABOVE: Hubble image of Makemake and its moon

BELOW: Makemake is located in the Kuiper Belt in the outer Solar System

COMPOSITION

FROZEN METHANE AND ETHANE ON THE SURFACE

A THIN ATMOSPHERE, MOST LIKELY COMPOSED OF NITROGEN, MAY DEVELOP ON MAKEMAKE WHEN IT MAKES ITS CLOSEST APPROACH TO THE SUN

NEWS FROM THE OUTER SOLAR SYSTEM

DWARF PLANET LACKS AN ATMOSPHERE

In 2011, distant starlight gave astronomers the best look yet at Makemake. Although this icy world currently lacks an atmosphere, there's still a chance it could form one when it approaches the point in its orbit closest to the Sun. Makemake passed directly in front of the distant star NOMAD 1181-0235723. This eclipse, or occultation, helped backlight the icy world, helping researchers pin down Makemake's size, shape and surface properties better than ever.

Such occultations are extremely difficult to predict and observe. For comparison, these worlds are so distant they appear about the same size "as that of a coin seen at a distance of 50 kilometres (30 miles) or smaller," said planetary scientist José Luis Ortiz Moreno. "But thanks to our hard work and to an important international collaboration, we were able to beat all the difficulties." At most, Makemake's atmosphere is 80 million to 250 million times thinner than Earth's at sea level, the researchers calculated. Still, there might be patches of atmosphere overlying warmer regions on its surface, such as dark patches that absorb more sunlight.

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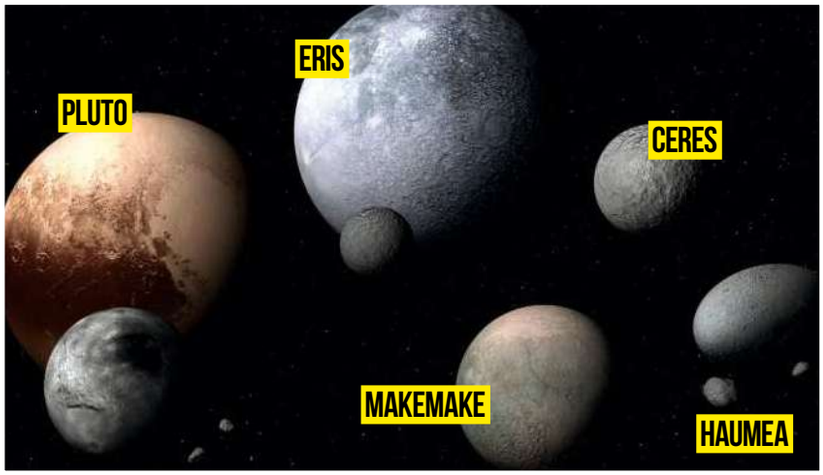

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MEET THE SOLAR SYSTEM'S DWARF PLANETS

Pluto's demotion was spurred by the discovery of multiple large bodies orbiting even farther from the Sun than Pluto – particularly an object called Eris, which appeared to be bigger than Pluto. As a result, the IAU came up with a new definition of a planet: a body that circles the Sun without being another object's satellite, one large enough to be rounded by its own gravity and that has 'cleared its neighbourhood' of most other orbiting bodies.

Since Pluto shares orbital space with lots of other objects out in the Kuiper Belt – the ring of icy bodies beyond Neptune – it didn't make the cut. So Pluto was newly classified as a dwarf planet, which tend to be smaller than 'true' planets and fall short on the 'clearing your neighbourhood' criterion. Although hundreds – or perhaps even thousands – more Solar System bodies may eventually join the list, the IAU officially recognises just five dwarf planets at the moment: Pluto, Eris, Haumea, Makemake and Ceres.

HAUMEA'S ELUSIVE RING

The rugby ball-shaped Haumea, which is surrounded by an almost perfectly circular ring of particles, is the most distant ringed object in the Solar System. Haumea's ring is too faint to be seen from Earth, so astronomers have turned to clues to find out more about these particles. Researchers with the São Paulo Research Foundation in Brazil have detailed the ring's size, shape and other characteristics by simulating the Haumea system on a computer. By simulating the ring's particles in different configurations around the dwarf planet and calculating which scenario would render the ring most stable, scientists were able to infer the likely qualities of the ring without ever looking at it directly.

Astronomers first spotted Haumea far beyond the orbit of Pluto in 2004; it was originally classified as a Kuiper Belt Object (KBO). The dwarf planet's two moons, Hi'iaka and Namaka, were first seen in 2005 by astronomers using the W. M. Keck Observatory in Hawaii. As astronomers began to find more objects like Haumea floating in the outer region of the Solar System, the dwarf planet later became one of a handful of far-out bodies in this classification.

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GIANT CRATER ON CERES WITH BRIGHT SPOTS MAY BE THE MOST FASCINATING PLACE IN THE SOLAR SYSTEM

For a few months in 2018, as NASA's Dawn spacecraft used up its last drops of fuel, it gave scientists an incredibly detailed look at one of the strangest places in the Solar System: Occator crater. That's the name of a massive impact site on the dwarf planet Ceres, tucked away in the asteroid belt. In the mission's last months, Dawn flew just 35 kilometres (22 miles) above the dwarf planet's surface and focused its energies on Occator crater. The data collected from Dawn suggests that cryovolcanism may have begun just 9 million years ago on Ceres, continuing for several million years. A series of bright deposits formed over that time from brine seeping out from Ceres' mantle through the upper layer of rock, with activity recorded as recently as a million years ago.

Another finding is a specific form of salt found so far only on Earth – and now on Ceres – that is particularly short-lived, on the scale of centuries. The combination suggests that the brines that deposited them on the surface must have done so very recently. These salts could also solve the puzzle of what's keeping Ceres relatively warm without gravitational tugging, and could be responsible for maintaining pockets of liquid within the dwarf planet.

LEFT: The spots reveal information about Ceres' geological past

BELOW: A rendering of sunrise on the reddish-brown dwarf planet

MAKEMAKE TIMELINE

- **Date:** 4.5 billion years ago
  Activity: Makemake formed alongside other icy worlds in the history of our Solar System.
- **Date:** March 2005
  Activity: Makemake is observed for the first time by scientists Mike Brown, Chad Trujillo and David Rabinowitz at the Palomar Observatory in California.
- **Date:** 19 July 2008
  Activity: Makemake is officially named by the International Astronomical Association.
- **Date:** April 2011
  Activity: Astronomers determined Makemake had no atmosphere after observing its occultation of a faint star.
- **Date:** April 2016
  Activity: NASA announces the discovery of Makemake's moon MK 2.

MAKEMAKE BY NUMBERS

6 HOURS 20 MINUTES
How long it takes sunlight to reach Makemake

715 KILOMETRES
Makemake's radius

1,300
How many times fainter MK 2 is compared to Makemake

12
Estimated length of time, in days, MK 2 takes to complete an orbit of Makemake

45.8AU
Average distance Makemake is from the Sun in astronomical units, with one AU being the Earth-Sun distance

5
The current number of recognised dwarf planets in our Solar System

"LIKE ALL THE KNOWN DWARF PLANETS BUT CERES, MAKEMAKE TRAVELS THROUGH THE KUIPER BELT"

'FARFAROUT'

OFFICIALLY THE SOLAR SYSTEM'S MOST DISTANT OBJECT

THIS RECENTLY DISCOVERED TRANS-NEPTUNIAN OBJECT LIES SOME 140 ASTRONOMICAL UNITS FROM THE SUN

The planetoid dubbed 'FarFarOut' was first detected in 2018 at an estimated distance of 140 astronomical units (AU) from the Sun – farther away than any object had ever been observed. One AU is the average Earth-Sun distance – about 93 million miles, or 150 million kilometres. For perspective, Pluto orbits at an average distance of about 39 astronomical units.

FarFarOut's inherent brightness suggests a world roughly 400 kilometres (250 miles) wide, barely enough to qualify for dwarf planet status. But the size estimate assumes the world is largely made of ice, and that assumption could change with more observations.

Speaking of more observations, the detection team has now collected enough additional data to confirm the existence of FarFarOut and nail down its orbit. As a result, the planetoid just received an official designation from the Minor Planet Center in Cambridge, Massachusetts, which identifies, designates and computes orbits for small objects in the Solar System.

That new designation, announced on 10 February in a Minor Planet Center electronic circular, is 2018 AG37. FarFarOut will also receive a catchier official moniker down the road. "A single orbit of FarFarOut around the Sun takes a millennium," discovery team member David Tholen, an astronomer at the University of Hawaii, said. "Because of this long orbital period, it moves very slowly across the sky, requiring several years of observations to precisely determine its trajectory."

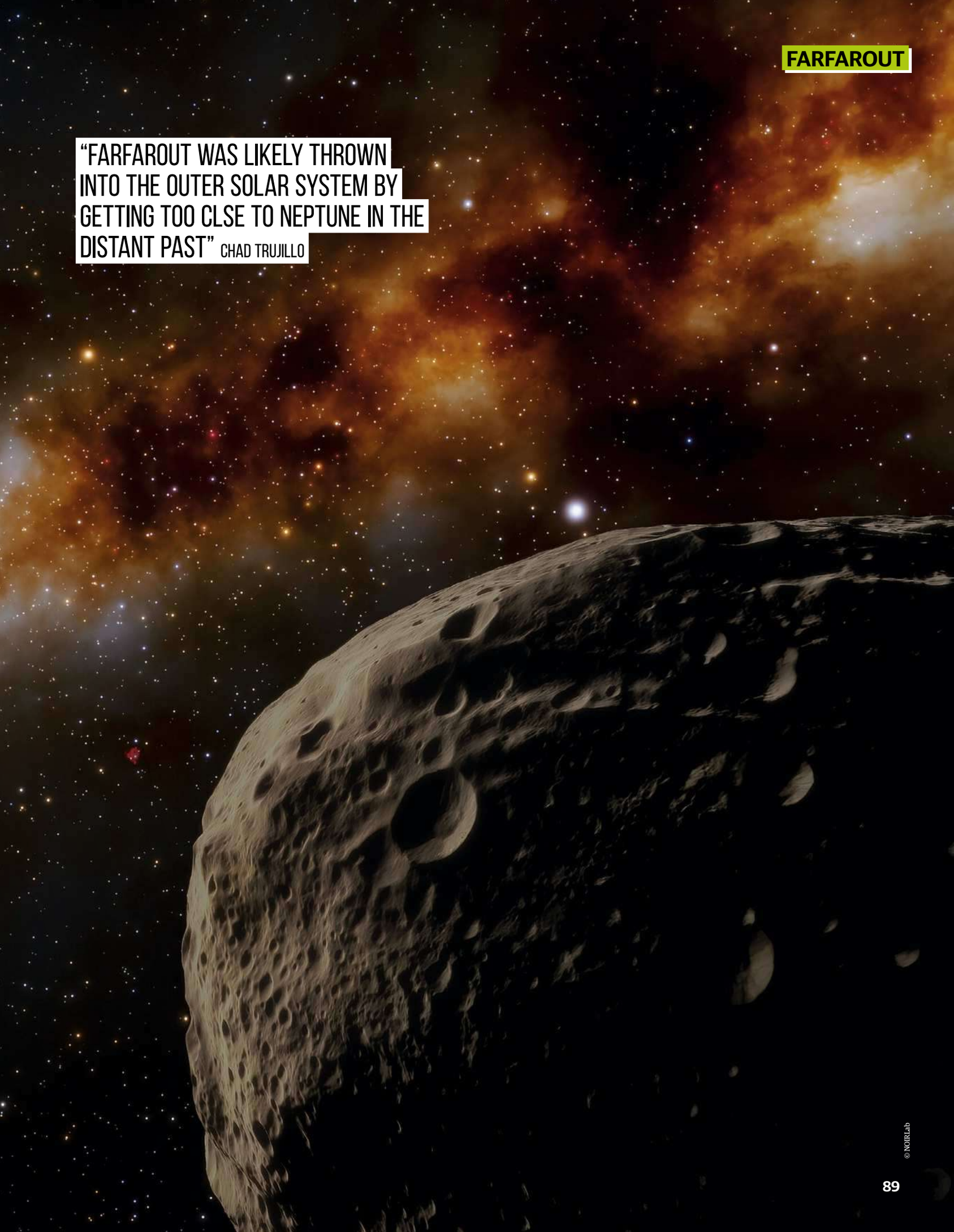
Astronomers spotted FarFarOut using the Subaru Telescope on Mauna Kea in Hawaii and traced its orbit using the Gemini North and Magellan telescopes. "Only with the advancements in the last few years of large digital cameras on very large telescopes has it been possible to efficiently discover very distant objects like FarFarOut," co-discoverer Scott Sheppard, a Solar System small bodies scientist at the Carnegie Institution for Science, said.

FarFarOut is currently about 132 AU from the Sun, the researchers determined. And its orbit is now known to be very elliptical, swinging between extremes of 27 and 175 AU, thanks to gravitational sculpting by Neptune. "FarFarOut was likely thrown into the outer Solar System by getting too close to Neptune in the distant past. FarFarOut will likely interact with Neptune again in the future, since their orbits still intersect," Chad Trujillo, an exoplanet astronomer at Northern Arizona University from the National Science Foundation's NOIRLab, said.

Because Neptune plays such a large role in FarFarOut's life, the planetoid likely cannot help astronomers in the hunt for Planet Nine, the big hypothetical world that some astronomers think lurks unseen in the far outer Solar System. Planet Nine's existence has been inferred from its putative gravitational influence on small bodies very far from the Sun, whose orbits cluster in odd and interesting ways. But the small worlds that astronomers look to as breadcrumbs in the Planet Nine search are free of Neptune's influence, unlike FarFarOut.

The team that spotted FarFarOut is well known for peering deep into the dark and frigid outer Solar System. In 2018 the researchers also found distant object Farout and a faraway dwarf planet nicknamed 'the Goblin'. FarFarOut's distance record refers to its current location. There are a number of other objects, such as the dwarf planet Sedna, whose orbits take them much farther away from the Sun than FarFarOut's maximum orbit. And scientists think there are trillions of comets in our Solar System's Oort Cloud, which begins about 5,000 AU from the Sun.

RIGHT: The small, far-flung world is thought to be comprised of ice and rock, like a comet



"FARFAROUT WAS LIKELY THROWN INTO THE OUTER SOLAR SYSTEM BY GETTING TOO CLSE TO NEPTUNE IN THE DISTANT PAST" CHAD TRUJILLO

IS THERE A PLANET NINE?

MIKE BROWN IS THE MAN WHO KILLED PLUTO, BUT HAVE THE TABLES TURNED TO LEAVE HIS OWN THEORY OF A NINTH WORLD IN DOUBT?

Mike Brown is a professor of planetary astronomy at the California Institute of Technology (Caltech), but he is also known as the 'Pluto killer'. It was 2006 when the International Astronomical Union downgraded Pluto's planetary status to that of a dwarf. Brown led the charge following his discovery of Eris in January the previous year, and it meant the Solar System was back to having just eight planets. For some, the move was unthinkable. Dr Alan Stern, who headed up the New Horizons mission that sent a spacecraft to Pluto, was particularly angry. Yet it had been coming since 1992, when a new object was discovered in what became known as the Kuiper Belt beyond the orbit of Neptune.

What few saw coming, however, was the emergence of a new candidate for the ninth planet. As if to rub salt in the wounds of those who felt Pluto's status should be reinstated, it was Brown – along with a fellow professor of planetary science at Caltech, Konstantin Batygin – who put the theory forward ten years later based on observations of six extreme trans-Neptunian objects, or ETNOs.

One of them, Sedna, is 40 per cent the size of Pluto, and it behaves in an strange way. Rather than forming an elliptical ring around the Sun as expected, this large planetoid in the outer reaches of the Solar System – some three times farther away than Neptune – has an exceptionally long and elongated orbit. Taking about 11,400 years to complete its cycle, it will at some point be 76 astronomical units (AU) from the centre of our Solar System – that's 76 times the distance between Earth and the Sun – but it will swing out to more than 900 AU.

What's more, it's not alone. Brown and Batygin observed a cluster of six other ETNOs with similar orbits, and they tilt on their axis in the same direction. They don't appear to be as affected by the known giant planets in our Solar System as other trans-Neptunian objects, so the two scientists came up with an explanation.

According to Brown and Batygin's calculations and modelling, the unexpected clustering of objects is due to the gravitational pull of an as-yet-undiscovered ninth planet that is between 13 and 26 times farther out than Neptune. This hypothetical celestial body would have a predicted mass between five and ten times that of Earth. Its orbit would be elongated, ranging between 400 and 800 AU.

It's an exciting proposition, yet one that has not gone unchallenged. A study led by Kevin Napier at the University of Michigan has cast doubt on the theory. By observing 14 far-off rocky bodies discovered by three surveys – five each from the Dark Energy Survey and the Outer Solar System Origins Survey and a further four picked up by astronomers Scott Sheppard, Chad Trujillo and David Tholen – they say there is no evidence of ETNO clustering that would firmly indicate the existence of an extra planet.

> "IT WOULD HAVE BEEN MORE EXCITING IF OUR FINDINGS SHOWED STRONG EVIDENCE FOR CLUSTERING, AND THUS FOR PLANET NINE" KEVIN NAPIER

PLANET NINE
BY THE NUMBERS

5-10
times the mass of Earth

2-4
times the radius of Earth

400-800
times farther from the Sun than Earth

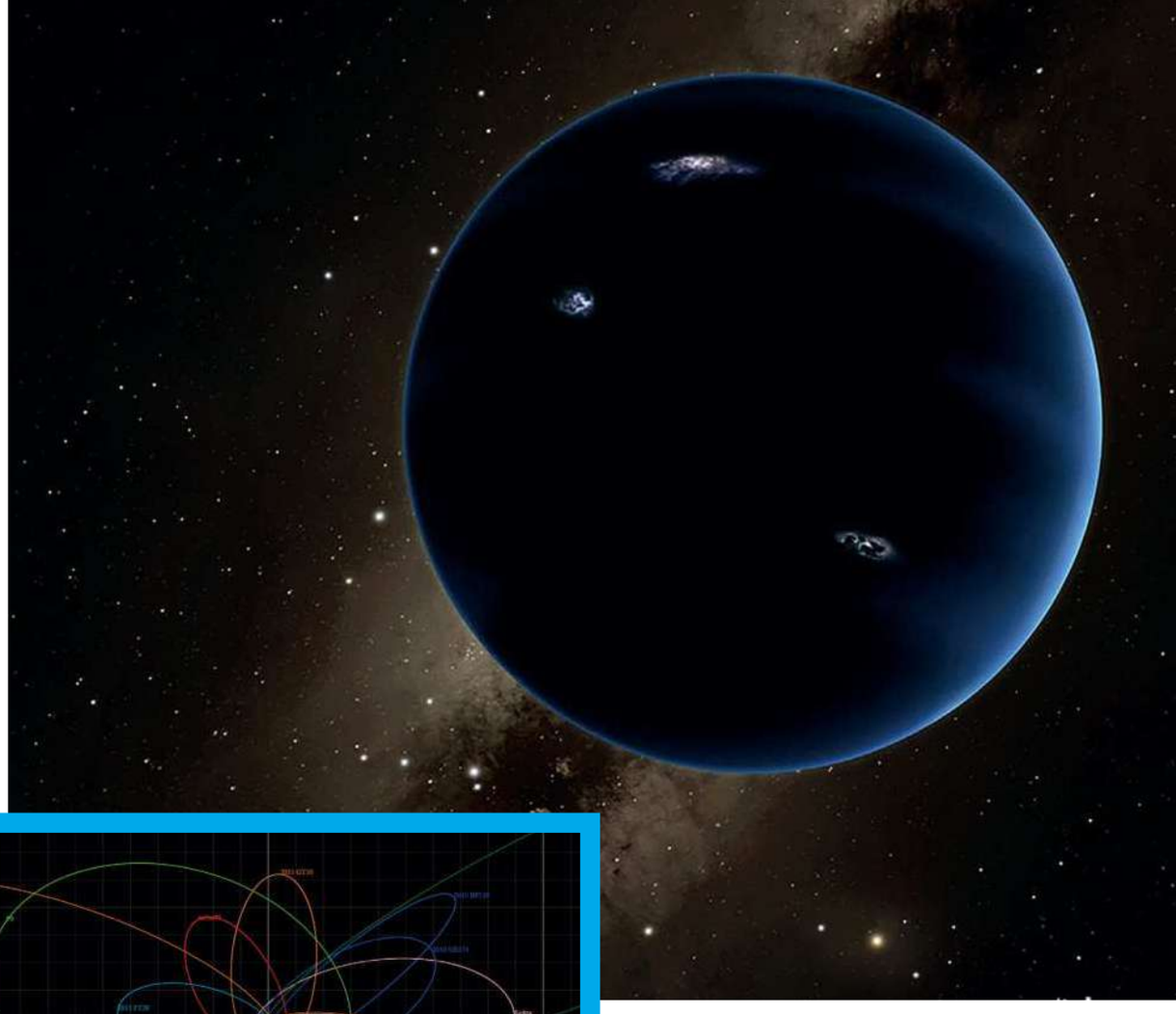
0
Number of observations

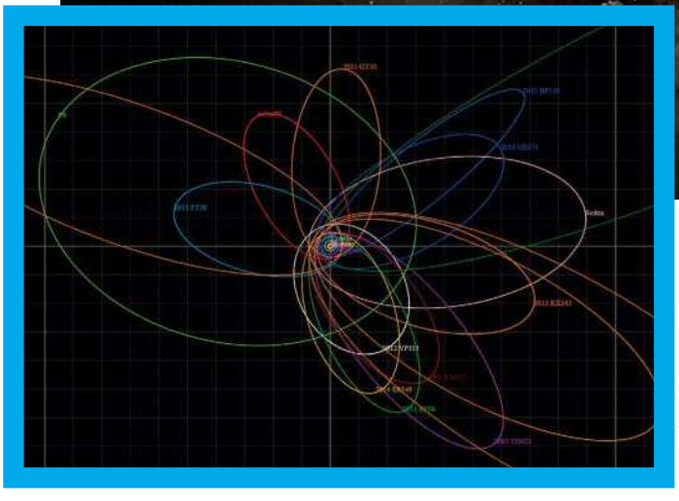
6
Number of extreme trans-Neptunian objects which appear affected by Planet Nine

10,000-20,000
Years to make a full orbit of the Sun

20 YEARS
Time Mike Brown estimates it would take for a probe to reach the planet

0.2-0.5
The hypothesised eccentricity of Planet Nine's orbit





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TOP: An artist's concept of Planet Nine in orbit far from the Sun

ABOVE: The original six ETNOs used by Brown and Batylin to hypothesise about Planet Nine, along with the planet's theorised orbit (in green) and eight other ETNOs

Instead, the group posits that the findings by Brown and Batygin are due to observational bias. In other words, the new research reckons that Planet Nine's apparent existence is mainly based on the direction in which the two scientists' telescopes looked. Since Brown and Batygin observed just a small section of sky, the selection of ETNOs was limited. This, says Napier, weakens the case.

"Simulations have shown that Planet Nine causes the orientations of the ETNOs' orbits to cluster on timescales comparable to the age of our Solar System," Napier highlights. "There are now on the order of a dozen known ETNOs that appear to exhibit this clustering, and if you look at the data, the clustering appears to be rather robust.

"But you cannot simply look at the data and draw robust conclusions because of this effect called observational bias," Napier continues. "It takes into account factors such as where you pointed the telescope, when you took the observation and how faint of an object the telescope was able to see.

"Because the ETNOs are on exceptionally long, skinny orbits, they can only be seen for a very short segment, when they are closest to the Sun. This makes the observational biases present in their discovery rather severe. Until our study, nobody had performed a meta-analysis on all of the ETNOs discovered by surveys with calculable biases. It turns out that when you properly account for these observational biases, the population of ETNOs we observe is fully consistent with a uniform – rather than a clustered – underlying distribution."

In carrying out their research, Napier and his team decided to look at ETNOs that were not studied by Brown and Batygin. Those original six were discovered by surveys with unknown biases, "so we were unable to properly analyse them," explains Napier. "We wanted to test an independent sample because in a larger, better controlled sample, you would expect the significance of the clustering to either stay the same or to increase. We found the significance decreased."

Napier's team did include two of the original six objects after their main analysis, however, giving them a total of 16. "We still found that the observations were consistent with a uniform underlying distribution," he adds. But does that mean talk of a Planet Nine is off the table?

Causing some confusion about the conclusion is the title of Napier's academic paper, entitled: No Evidence for Orbital Clustering in the Extreme Trans-Neptunian Objects. It jars with

"THE SURVEY-SIMULATION APPROACH CANNOT BE USED TO DISTINGUISH CLUSTERED OR UNCLUSTERED ORBITS"

KONSTANTIN BATYGIN

© Caltech

the content of the work itself, and Batygin has not been slow to seize on this. "The Napier et al study does not actually draw the conclusion in the title," he tells us. "The work demonstrates that the survey-simulation approach cannot be used to distinguish between clustered or unclustered orbits, and this is not particularly surprising. Heavily biased surveys like the Outer Solar System Origins Survey or Dark Energy Survey are very hard to de-bias, and given the limited number of detections in each survey, the fact that survey-simulation cannot rule out any distribution is not perplexing."

Brown agrees wholeheartedly. "If you read the paper really carefully, then the correct statement from the Napier analysis would be something like: 'Our survey was very biased, and this could not detect clustering at the level previously detected.' It's a big leap that there is no clustering, and it's one they don't make in the paper, but do in interviews. In fact, if we add their new objects to our full dataset instead of using their much more limited dataset, the clustering actually improves."

Napier admits that the work doesn't rule out the existence of Planet Nine, saying only that it has "certainly weakened the case for it". He says he would have preferred the conclusion to have backed the original hypothesis. "It would have been more exciting if our findings showed strong evidence for clustering in the ETNOs, and thus for Planet Nine," he says.

"That being said, we still find our results exciting," he adds. "Even if it turns out that Planet Nine doesn't exist, there must be some

ORBITS IN THE OUTER SOLAR SYSTEM

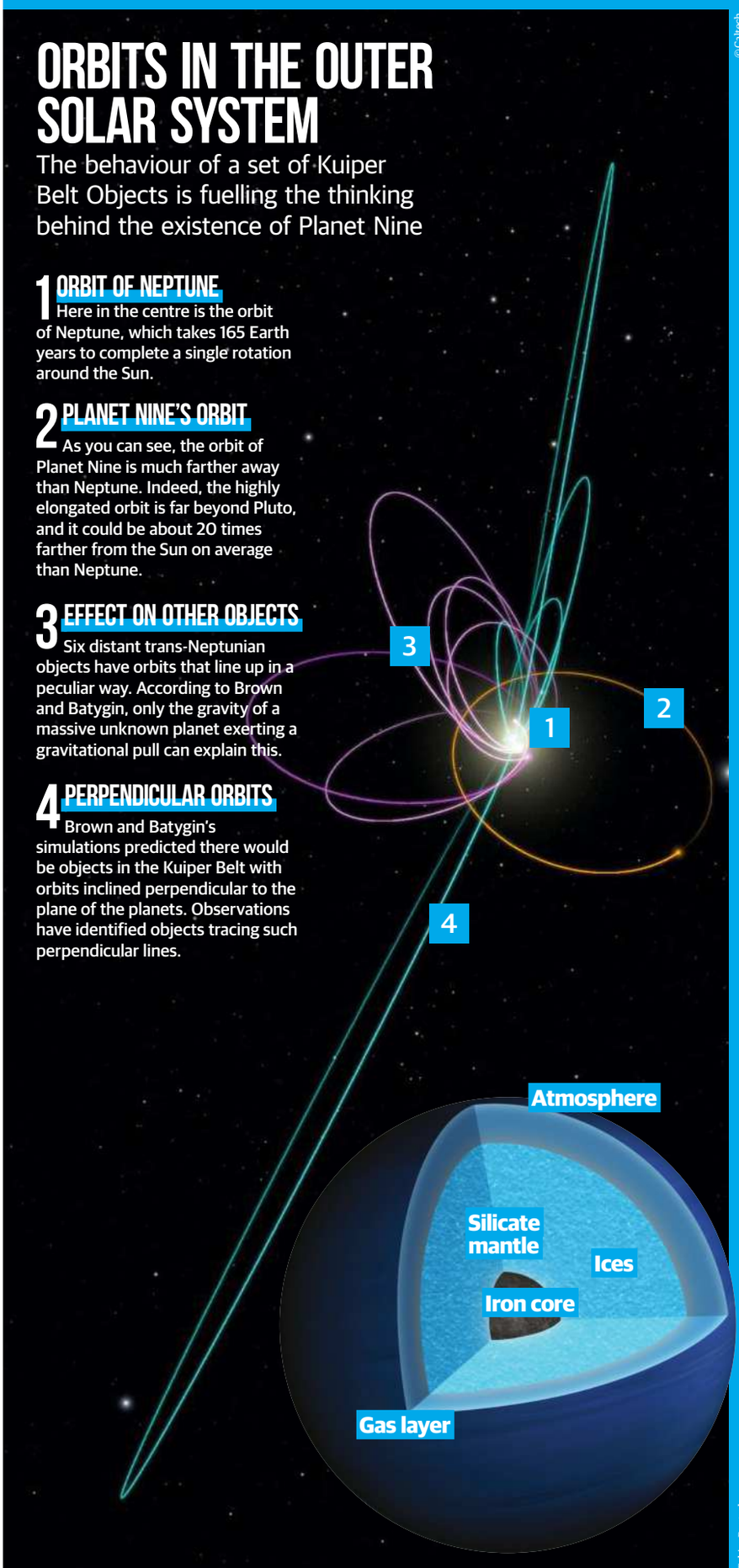
The behaviour of a set of Kuiper Belt Objects is fuelling the thinking behind the existence of Planet Nine

1 ORBIT OF NEPTUNE
Here in the centre is the orbit of Neptune, which takes 165 Earth years to complete a single rotation around the Sun.

2 PLANET NINE'S ORBIT
As you can see, the orbit of Planet Nine is much farther away than Neptune. Indeed, the highly elongated orbit is far beyond Pluto, and it could be about 20 times farther from the Sun on average than Neptune.

3 EFFECT ON OTHER OBJECTS
Six distant trans-Neptunian objects have orbits that line up in a peculiar way. According to Brown and Batygin, only the gravity of a massive unknown planet exerting a gravitational pull can explain this.

4 PERPENDICULAR ORBITS
Brown and Batygin's simulations predicted there would be objects in the Kuiper Belt with orbits inclined perpendicular to the plane of the planets. Observations have identified objects tracing such perpendicular lines.



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FURTHERING THE CASE FOR PLANET NINE

American astronomer Mike Brown has worked on the hypothesis of another world for the last five years

Some scientists have been unable to create a computer simulation that accounts for the clustered trans-Neptunian objects which form the basis of the theory of Planet Nine. Does this cast doubt over its existence in your mind?
Many groups have reproduced computer simulations that make the Planet Nine cluster. The physics is well understood. It is neither difficult nor mysterious.

Would you say the suggestion that you observed a small portion of the sky during a specific part of the year at a specific time of day is valid?
I haven't heard that suggestion. Our survey is the only one that doesn't do that. The others are much more limited.

How strong is the evidence for a Planet Nine in light of the recent study?
The Napier paper neither adds nor subtracts to the Planet Nine hypothesis, though adding in the new objects would strengthen the hypothesis if we combined it with our full dataset - we haven't done this thoroughly yet, though. I would say the Planet Nine hypothesis is as strong as it used to be.

explanation for the orbital behaviour of some of the strangest objects in our Solar System. Examples of such anomalies include Kuiper Belt Objects on highly inclined orbits and objects that never come closer to the Sun than twice the distance of Neptune. Mysteries like this are what keep us going."

As far as Batygin is concerned, the mystery surrounding Planet Nine is still in favour of it being out there somewhere. He says it has been clear for a long time that individual surveys cannot overcome their own biases to rigorously determine clustering one way or another. "In fact, this has already been pointed out multiple times, and the Napier et al analysis combines the well-characterised surveys, but still finds the same answer," he says. "For this reason, in order to determine the 'false-alarm probability' of the clustering, it makes sense to instead do an observability analysis which takes advantage of the full dataset to determine statistical significance." Batygin says he did exactly this in a paper with Brown published in 2019: "The analysis demonstrates that the chances that the data are not clustered is only 0.2 per cent."

By this, Batygin is theorising that the chance of clustering happening naturally without any gravitational pull from a body such as Planet Nine is extremely slim. What's more, as well as the clustering of orbits, the ETNOs with perihelia beyond 50 AU are too sufficiently distanced from Neptune to experience significant gravitational perturbations from it, so it points to something having an effect.

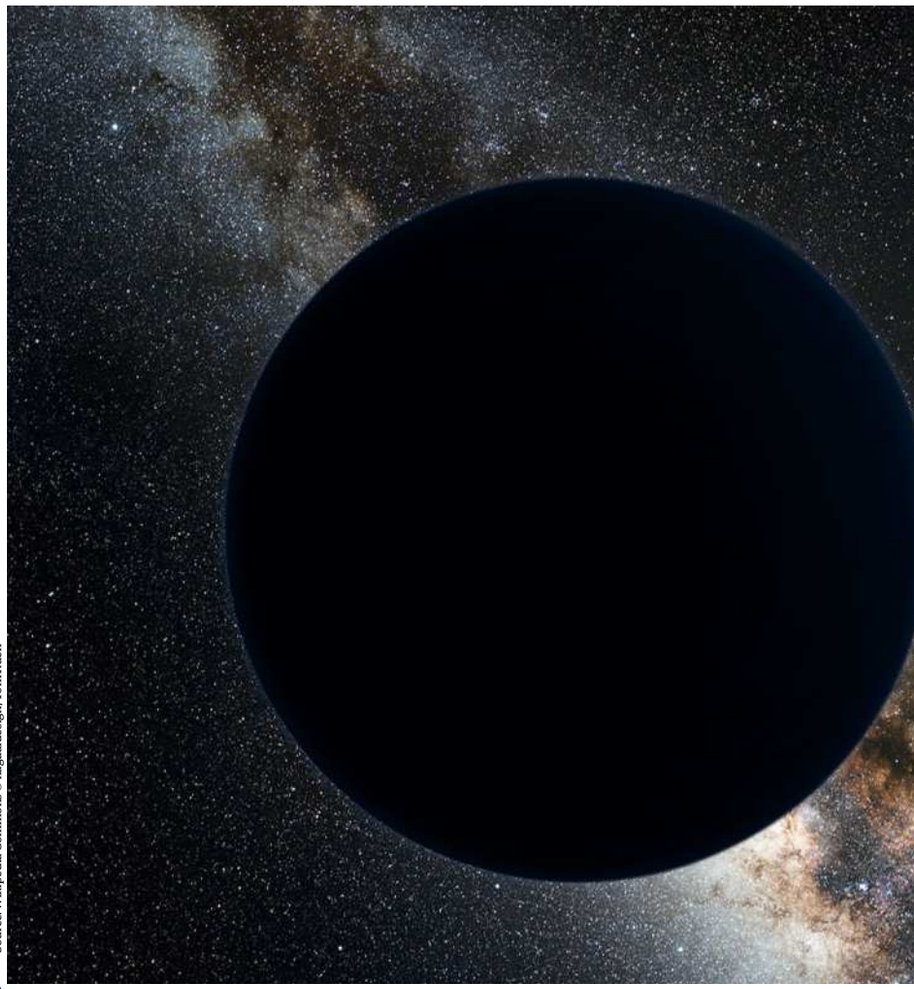
"An important point to understand is that the Planet Nine hypothesis is not just one thing," Batygin says. "There is a collection of lines of evidence that all paint the same picture: clustering of the apsidal lines, grouping of the angular momentum vectors, detached perihelia of long-period Kuiper Belt Objects, excitation of distant Kuiper Belt Objects to high inclinations and generation of the retrograde centaur population of the outer Solar System. The fact Planet Nine ties all these outer Solar System anomalies together gives me some confidence that we are on the right track."

In that sense, he doesn't perceive the study by Napier to have much of an effect on the original hypothesis. "There is one more very important point to understand, which routinely gets lost in translation," he continues. "The distant Kuiper Belt is made up of stable as well as unstable objects, and in the Planet Nine story, it doesn't matter what the unstable objects do.

"If you look at the data, the stable, high-perihelion objects cluster very well, while the unstable objects are all over the place. That's what the theoretical model predicts too. You can

RIGHT: An artist's impression of Planet Nine with the Sun in the very far distance, circled by the orbit of Neptune

BELOW: Brown bears the nickname of 'Pluto killer'



Source: Wikipedia Commons © naguladesign; Tom Ruen

imagine a whole range of observational biases that can cause clustering, but it's impossible to bias based on dynamical stability. Because the Napier et al dataset is roughly half stable, it's not a huge surprise they cannot prove that it's clustered." But does that still mean it has to be a planet causing the clustering? With the theory suggesting that gravity is at play, planets are not the only objects able to exert a gravitational pull. Dark matter or a primordial black hole are among the alternative suggestions.

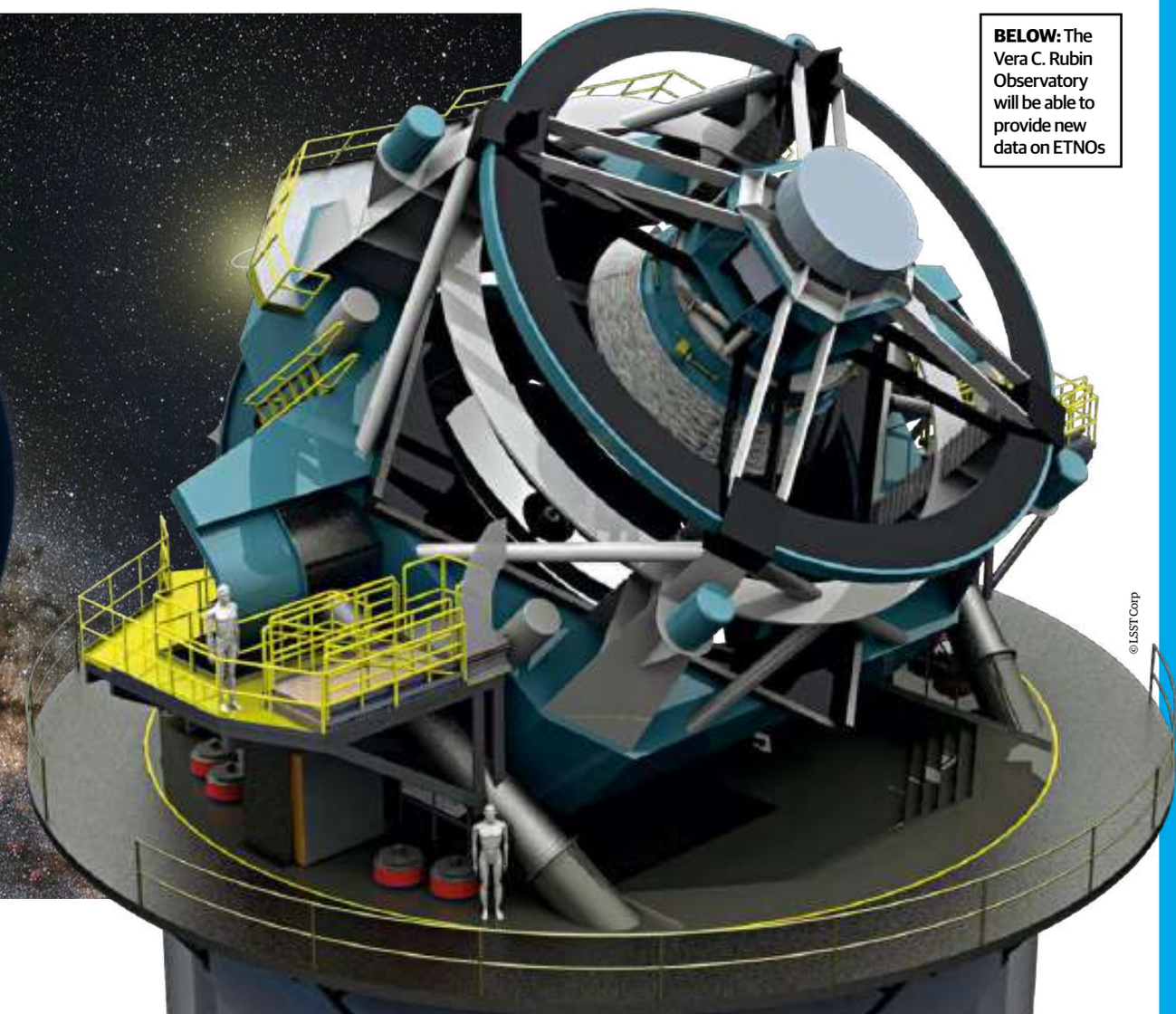
Napier reckons a planet would be the most likely explanation, so long as it's one day proved that the clustering is persistent. "It's hard to imagine it being caused by a dynamical mechanism other than Planet Nine if the clustering is persistent and not transient," he says. But recent work has shown that it's possible we are observing a temporary clustering of the ETNOs. It's clear more work needs to be done.

Certainly, the hypothesis of a Planet Nine is not going away any time soon. "I'm still quite optimistic that Planet Nine exists," says Batygin, with the use of the word 'quite' being notable. Napier, on the other hand, concludes: "I'm hopeful, but not optimistic. It might be there; it might not." Its existence would make life easier, but only one thing would really nail it. "Direct detection would be best," says Batygin, "and the answer to anything short of that is basically more data."

Napier agrees, and both are pinning their hopes on the Vera C. Rubin Observatory in Chile, which is coming online soon in 2023. The Legacy Survey of Space and Time at the observatory means the census of trans-Neptunian objects will expand substantially. One of the reasons why sufficient data has been hard to come by so far is access to telescopes and a focus on ETNOs in particular. Estimates are that the survey will discover more ETNOs, and with that data we'll be able to make a compelling statement.

One thing's for sure, there's a willingness for a discovery. In truth, most scientists would love to actually find Planet Nine. "A new planet would be extremely cool, and it would solve a lot of anomalies that we don't understand about our Solar System," Napier says. "But we have to entertain the possibility that there is no Planet Nine and continue searching for alternate explanations of those anomalies." We can only wait with bated breath.

David Crookes
Science and technology journalist
David has been reporting on space, science and technology for many years, has contributed to many books and is a producer for BBC Radio 5 Live.



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BELOW: The Vera C. Rubin Observatory will be able to provide new data on ETNOs

THE THEORIES

What could be affecting the extreme trans-Neptunian objects?

1 PLANET NINE

Modelling in 2016 by Brown and Batygin at Caltech hypothesised that six ETNOs had similar orbits because a large planet well beyond Neptune was exerting a massive gravitational pull on them. The scientists are sticking to this theory, and 19 ETNOs are now shown to exhibit a similar tilt and eccentric orbital pattern. This theory has yet to be proved or disproved.

© Getty

2 THERE'S NO CLUSTERING

According to a recent study headed by Napier, it is possible that there is no clustering in the first place. Other work suggests that any clustering could be temporary, and if either of these are the case then the likelihood of any gravitational pull being exerted is ruled out, thereby leaving any case for a Planet Nine severely dented.

© NASA

3 SOMETHING ELSE IS AT PLAY

If the ETNOs are being affected by something, does it have to be a planet? Scientists are looking into the possibility of a primordial black hole – a black hole which formed soon after the Big Bang – but these this is hypothetical. Dark matter is another theory, but again it's one hypothetical explaining another.

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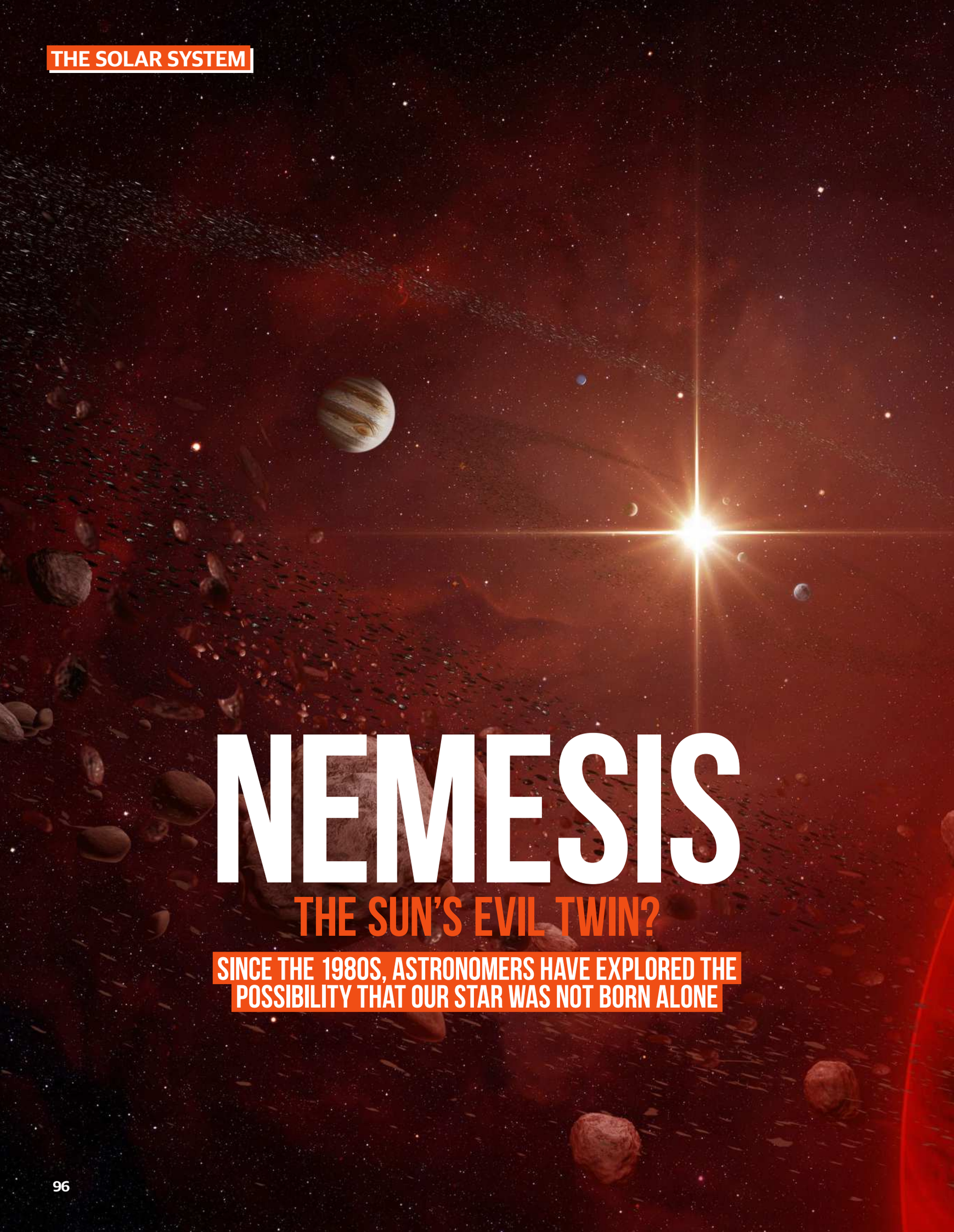


NEMESIS

THE SUN'S EVIL TWIN?

SINCE THE 1980S, ASTRONOMERS HAVE EXPLORED THE POSSIBILITY THAT OUR STAR WAS NOT BORN ALONE

What do you get if you cross the dinosaurs with millions of comets and an evil twin of our Sun that has not only wreaked havoc on Earth multiple times but has long been hidden from view? Anxious? Fearful? Maybe both? For while it may sound like a terrible joke. The intriguing punchline once caused some alarm – and raised a mystery that had astronomers hooked for quite some time.

Welcome to Nemesis, the Sun's hypothetical long-lost companion which has been speculated to be circling in the edges of the Solar System. Proposed by Richard A. Muller, an American physicist and professor of physics at the University of California, Berkeley, it gained some ground in the 1980s with the suggestion that it was behind a series of mass extinction events here on Earth.

The theory grew from a 1983 study by two palaeontologists, David Raup and Jack Sepkoski. They had analysed the extinction rates of 27,000 marine animals which perished during the past 250 million years and pointed towards five mass wipeouts since the Late Permian era, in which more than 75 per cent of species disappeared. They went on to suggest that these catastrophic extinction events were uniformly spaced, taking place every 26 million years, but scientists could not quite fathom why.

Various studies emerged looking at phenomena on Earth, but the belief that a large asteroid wiped out the dinosaurs – a hypothesis by Luis and Walter Alvarez in 1980 – suggested extraterrestrial forces could be at play. It was on this basis that Muller came up with the idea that the comet which smashed into Earth 66 million years ago had been among a humongous group of bodies disrupted by a theoretical red dwarf star. He said it affected the orbits of these objects and sent them hurtling towards our Sun, smashing into whatever they encountered.

That in itself would have been rather eye-catching, but here is where things became even more interesting. Muller's theory postulated that this star was the Sun's undetected companion – the 'evil twin' that we alluded to at the start of this article. He also reckoned the reason why there may have been this notable cycle of mass extinction events was because the red dwarf star was regularly putting itself among the set of icy rocks that make up the equally theoretical Oort Cloud in the outermost reaches of the Solar System.

It would do so every 26 million years, he says, neatly accounting for the calculated apocalyptic timeframe on Earth. But in order to do this the red dwarf star needed to be in a 1.5 light year elliptical orbit, periodically bringing it closer to the Oort Cloud and sending comets hurtling our

way. What's more, the theory continued, there was enough of a gravitational pull on the 'death star' by the Sun to prevent it from drifting away.

When Muller presented his hypothesis in 1984, it caused international controversy. The scientist was suggesting that the companion star was born at the same time as the Sun, and so was part of a binary star system – that is, one gravitationally bound and orbiting a common centre of mass. Yet in the last 35 years there has never been any sighting, even though it's not been for a lack of trying.

This is rather odd. Muller said Nemesis was likely to have a magnitude between seven and 12 and that it should be possible to view it through a small or medium telescope. But the Infrared Astronomical Satellite – the first space telescope to perform a survey of the night sky at infrared wavelengths – did not see any signs of it during the 1980s, while the Two Micron All-Sky Survey, or 2MASS, which surveyed the sky between 1997 and 2001, couldn't detect an additional star in the Solar System either.

The best shot was thought to be NASA's Wide-field Infrared Survey Explorer (WISE), which spotted a brown dwarf 7.2 light years away in 2014. But it wasn't Nemesis. In actual fact, when Kevin Luhman, an astronomer at Pennsylvania State University's Center for Exoplanets and Habitable Worlds, analysed images from WISE a year earlier in the outer Solar System, there was simply no sign of the companion star that Muller had proposed.

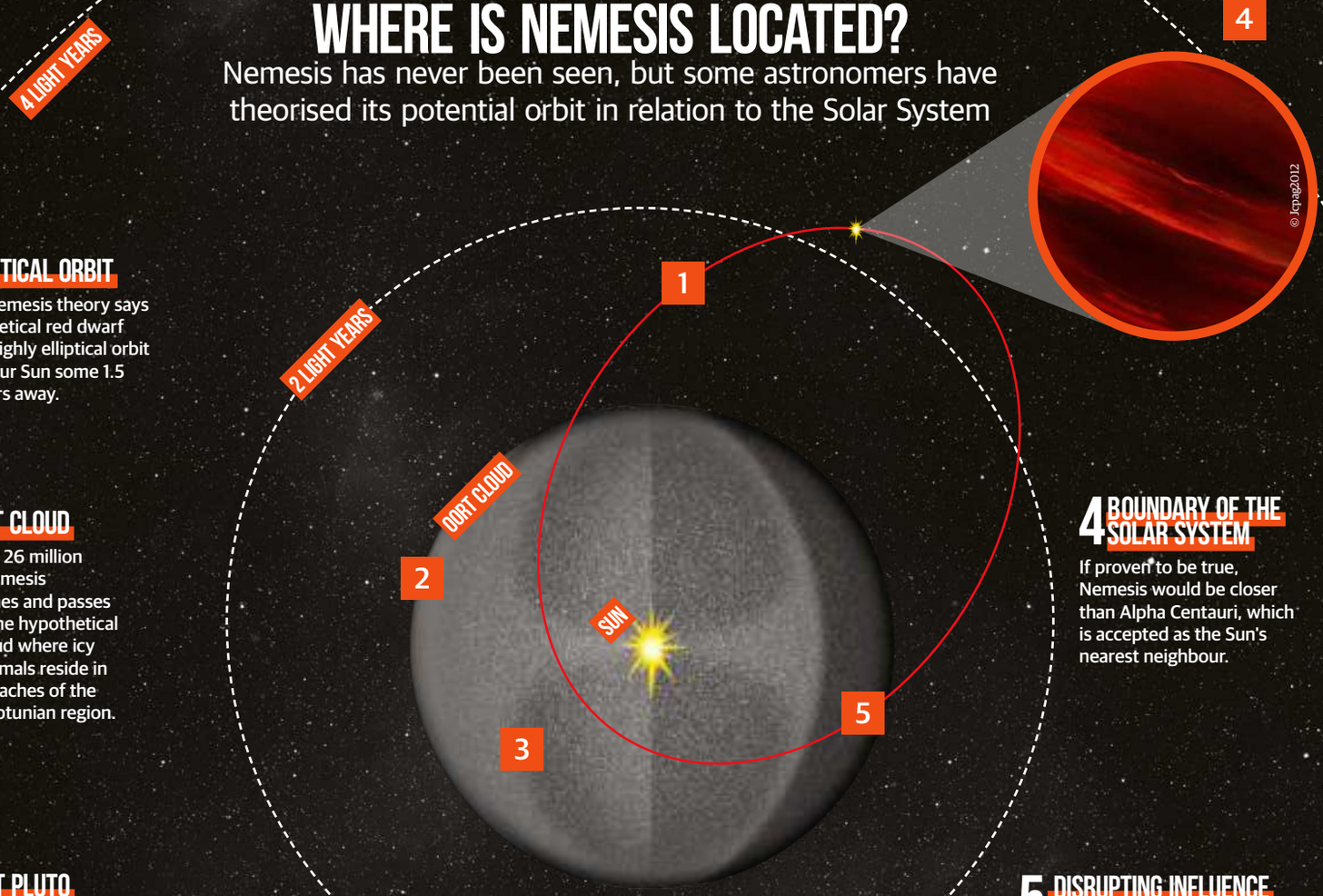
Instead, evidence kept stacking up against it. For starters, some astronomers questioned the inherent stability of Nemesis' proposed orbit. They said the star would come within the gravitational pull of other stars moving through the galaxy. Others cast doubt that extinction events follow a set cycle. "There is a tendency for people to find patterns in nature that do not exist," said Coryn Bailer-Jones from the Max Planck Institute for Astronomy in 2011. "Unfortunately, in certain situations traditional statistics plays to that particular weakness."

Bailer-Jones said the impact rate of asteroids and comets had been judged to be steadily increasing over the past 250 million years on the basis of the number of craters of different ages. But he argued that periodic variations could be ruled out: "From the crater record, there is no evidence for Nemesis," he concluded. "What remains is the intriguing question of whether or not impacts have become ever more frequent over the past 250 million years."

"STARS GENERALLY DO NOT FORM IN ISOLATION BUT ARE BORN TOGETHER IN GROUPS WITHIN CLOUDS OF GAS AND DUST OR NEBULAE" PAVEL KROUPA

WHERE IS NEMESIS LOCATED?

Nemesis has never been seen, but some astronomers have theorised its potential orbit in relation to the Solar System



1 ELLIPTICAL ORBIT

The Nemesis theory says a hypothetical red dwarf takes a highly elliptical orbit around our Sun some 1.5 light years away.

2 OORT CLOUD

Every 26 million years, Nemesis approaches and passes though the hypothetical Oort Cloud where icy planetesimals reside in the far reaches of the trans-Neptunian region.

3 PAST PLUTO

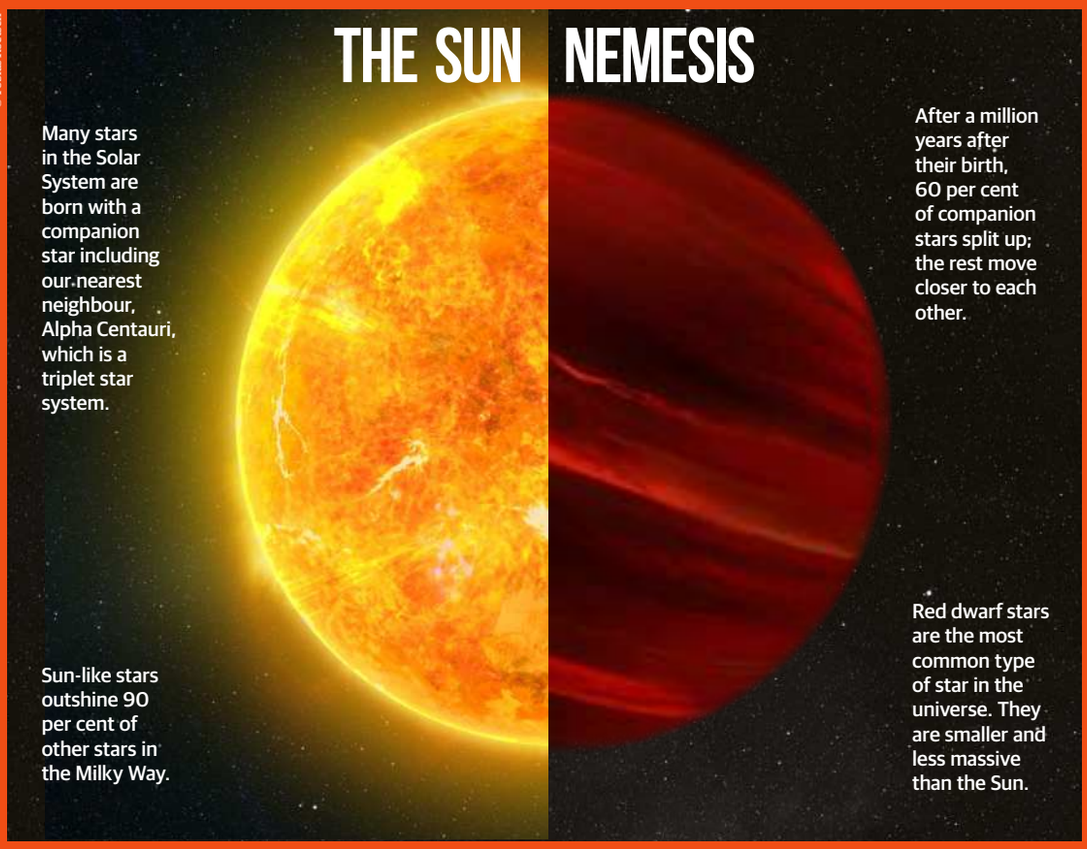
To put this into perspective, the Oort Cloud is way past the Kuiper Belt where Pluto orbits and also beyond the scattered disc, home to Eris.

4 BOUNDARY OF THE SOLAR SYSTEM

If proven to be true, Nemesis would be closer than Alpha Centauri, which is accepted as the Sun's nearest neighbour.

5 DISRUPTING INFLUENCE

When Nemesis passes through the Oort Cloud, it is said to have a disruptive effect on the bodies there, sending comets – which are ordinarily a light year away – hurtling towards the Sun.



ABOVE LEFT: An infrared sky survey by WISE failed to discover evidence of Nemesis

ABOVE RIGHT: Binary star systems are not uncommon – the closest to us is Alpha Centauri A and B, along with faint red dwarf C

On that basis it is surely a matter of 'case closed'. Here we have an intriguing idea that many of us would wish to be true, and yet in reality it sounds merely fantastical, with evidence that is flaky at best.

But that isn't telling the full story, and there has been a little matter of a dwarf planet called Sedna to consider, which some astronomers reckoned was additional proof of a twin for the Sun. It is, at 8 billion miles away, one of the most distant bodies in the Solar System, and it pursues an extremely elongated orbit. Discovered in 2003 by a team led by Mike Brown, an astronomer at the California Institute of Technology, it has certainly caught the imagination, but what does it really prove?

Well, there has been a theory that Sedna's wonky orbit could only be the result of a large and distant binary companion to the Sun pulling it out to such a distance. What else, scientists argue, could take the dwarf some 200-times further from the Sun than Neptune every 11,400 years? A study in 2015 seemed to lend credence to this argument when Lucie Jílková of Leiden Observatory in the Netherlands suggested a passing star flung it into interstellar space when the Sun was very young.

Yet today Brown tells us that he's not too certain about such theories. "Sedna's orbit is most likely caused by Planet Nine," he says, referencing a hypothetical planet in the outer region of the Solar System. In that sense, he believes there simply is no Nemesis.

"Very sensitive searches have failed to discover it," he affirms. "And, more importantly, the idea that there was periodic extinction appears to have

THE THEORIES

Is there really something big and influential somewhere out there causing mass extinctions?

THE NEMESIS THEORY

Richard A. Muller's theory suggests the Sun has a companion red dwarf star named Nemesis which has an unusual orbit and causes mass extinctions on Earth every 26 million years or so by having a chaotic impact on bodies in the Oort Cloud.

OUR DANGEROUS SUN

In 2008, a computer simulation by researchers at Cardiff University suggested our Solar System bounces up and down through the plane of the galaxy. Gravitational forces may dislodge comets from the Oort Cloud and send them cascading inwards.

A BROWN DWARF

Nemesis may not be a red dwarf, but a brown one. If that was the case then it would go some way towards explaining why astronomers have struggled to see it: brown dwarfs have a low intrinsic brightness, making them harder to discover.

OTHER PLANETS

There is an acceptance that there are other planets in the outer region of the Solar System. These have never been found, although computer simulations continue to rule in the possibility that they are out there exerting a gravitational influence.

GAS GIANT TYCHE

Scientific analyses suggest extinctions on Earth don't happen at regular, repeating intervals. Some astrophysicists propose a less disruptive gas giant in the Oort Cloud instead, dubbed Tyche – a Greek goddess who was the 'good sister' of Nemesis.

EVIDENCE FOR NEMESIS' EXISTENCE

Although yet to be proven, there are signs pointing towards a twin star

COMPANION STARS DO EXIST

We know that many stars have a companion, but in 2017 it was suggested that pretty much every star like the Sun had one. Indeed, Sarah Sadavoy and Steven Stahler argued the case for our Sun's companion, but said the partner separated shortly after formation.

OTHER BINARIES HAVE SIMILAR EFFECTS

In 2006, debris discs around two nearby stars were seen by researchers at the University of California, Berkeley, to resemble the Kuiper Belt with a sharp outer edge. It was proposed that a companion star causes this effect.

THE PRESENCE OF SEDNA

A trans-Neptunian object called Sedna has an unusual elliptical orbit around the Sun, and some say this is due to the influence of a potential binary companion. Sedna, with an orbit of 12,000 years, has been heralded as strong proof of a companion star for the Sun.

IT IS JUST TOO FAR AWAY

It's not evidence per se, but the Sun's companion star – at least following Sadavoy and Stahler's model – could now be thousands of light years away, which accounts for why it has never been seen.

"WE THINK THE SUN'S COMPANION DRIFTED AWAY BILLIONS OF YEARS AGO, WITHIN A MILLION YEARS AFTER THE SUN AND ITS COMPANION FORMED" STEVEN STAHLER

been a misinterpretation of the data. So I think there is both no Nemesis and no need to explain the data! I'm also pretty sure that Nemesis hasn't been a viable hypothesis for more than a decade."

Even so, the case remains open because the hypothesis of a companion star has actually moved on in recent years. While the original theory of Nemesis is perhaps not as strong today as it previously has been, there remains a firm belief in some quarters that the Sun was not born alone.

In 2017, Sarah Sadavoy and Steven Stahler carried out a study called 'Embedded Binaries and their Dense Cores'. Sadavoy, then a radio astronomer from the Max Planck Institute for Astronomy and Stahler, a theoretical physicist from the University of California, Berkeley, discussed how radio surveys of a giant molecular cloud filled with recently formed stars in the constellation Perseus led them to theorise that all Sun-like stars are likely to have been born with companions.

"I do believe this," Stahler tells All About Space. "The fact was already known for massive stars, and in 2017 Sarah Sadavoy and I provided strong evidence that low-mass stars like the Sun also tend to form with a companion." In the case of the Sun, this happened 4.5 billion years ago and meant it was born along the same lines as our nearest neighbour, Alpha Centauri, which is a triplet system.

"I believe there was probably a Nemesis a long time ago," he says, explaining that the mathematical model explaining the Perseus observations would only be possible if Sun-like stars are born with a companion. "We showed that probably all stars like ours form with companions," he tells us, "but that most, including the Sun, then lose those companions

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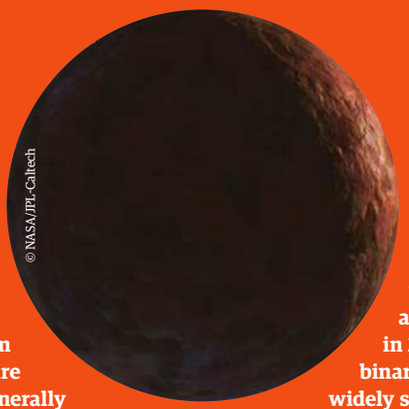
LEFT: Sarah Sadavoy and Steven Stahler say low-mass stars are always born with a companion but are likely to split, like the Sun

RIGHT: The cold dwarf planet Sedna is said reside at the outer edges of the known Solar System from where the Sun appears as an extremely bright star

BELOW: It was thought that the Sun's hypothesised twin, Nemesis, caused disruption to icy rocks in the Oort Cloud, causing chaos on Earth



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within the next million years."

The work built on that of Pavel Kroupa of the University of Bonn, whose computer simulations in 2011 led him to conclude that all stars are born as binaries. "Stars generally do not form in isolation but are born together in groups within clouds of gas and dust or nebulae," Kroupa wrote. "These stellar labour rooms produce binary star systems, which means that virtually all newborn stars have a companion. Most of these groups of stars disperse quickly so that their members become part of the galaxy."

In the case of Nemesis – or at least in the case of Sadavoy and Stahler's version of a companion Sun – the Sun's sibling escaped and mingled with other stars in the Milky Way. Stahler says he doesn't subscribe to the view that it then caused strong comet activity in the Oort Cloud. "20 years ago astronomers thought so, but few people believe that now," he affirms. Neither does he believe that the Sun has any influence over its companion.

"Muller's theory is different," he explains. "He postulated that the Sun currently has a companion on an eccentric orbit but, despite a lot of effort, this companion has never been found." Stahler is unsurprised that a form of Nemesis has never been discovered, though. "We think the Sun's companion drifted away billions of years ago, within a million years after the Sun and its companion formed," he highlights. "It could now be on the other side of the galaxy."

Such findings have wide implications, and they go to the heart of the origins of galaxies. In the case of Perseus there were 45 single-star systems, yet all but five of the 55 young stars in 24 multiple-star systems were binary. More than that, all of the widely separated binary systems – which are those with stars separated by more than 500 AU – were young systems.

"Our finding that most stars are born with companions is interesting for those of us who think about stellar birth," Stahler says. "Apparently our Sun, and also the Solar System, was born from an elongated gas cloud that formed another star – and perhaps another planetary system – as well. We see lots of such clouds, so studying them will tell us the conditions under which we formed."

It's the most compelling evidence that our Sun was once part of a binary star system, but the emphasis on 'once' cannot be stressed enough. As for the figure of 26 million years, well, that too is in doubt, with Adrian Melott and Richard Bambach having argued in their paper, Nemesis Reconsidered, that "the orbit of a distant companion to the Sun is expected to be perturbed by the galactic tidal field and encounters with passing stars, which will induce variation in the period".

What all of this means is that the Sun's potential twin is off the hook with regards to it being a mass-murderer, but there is great weight to Muller's assertion that the Sun was born with a companion. Unfortunately it'll be so far away now that we're unlikely to ever see it, it's history perhaps forever keeping us in the dark.

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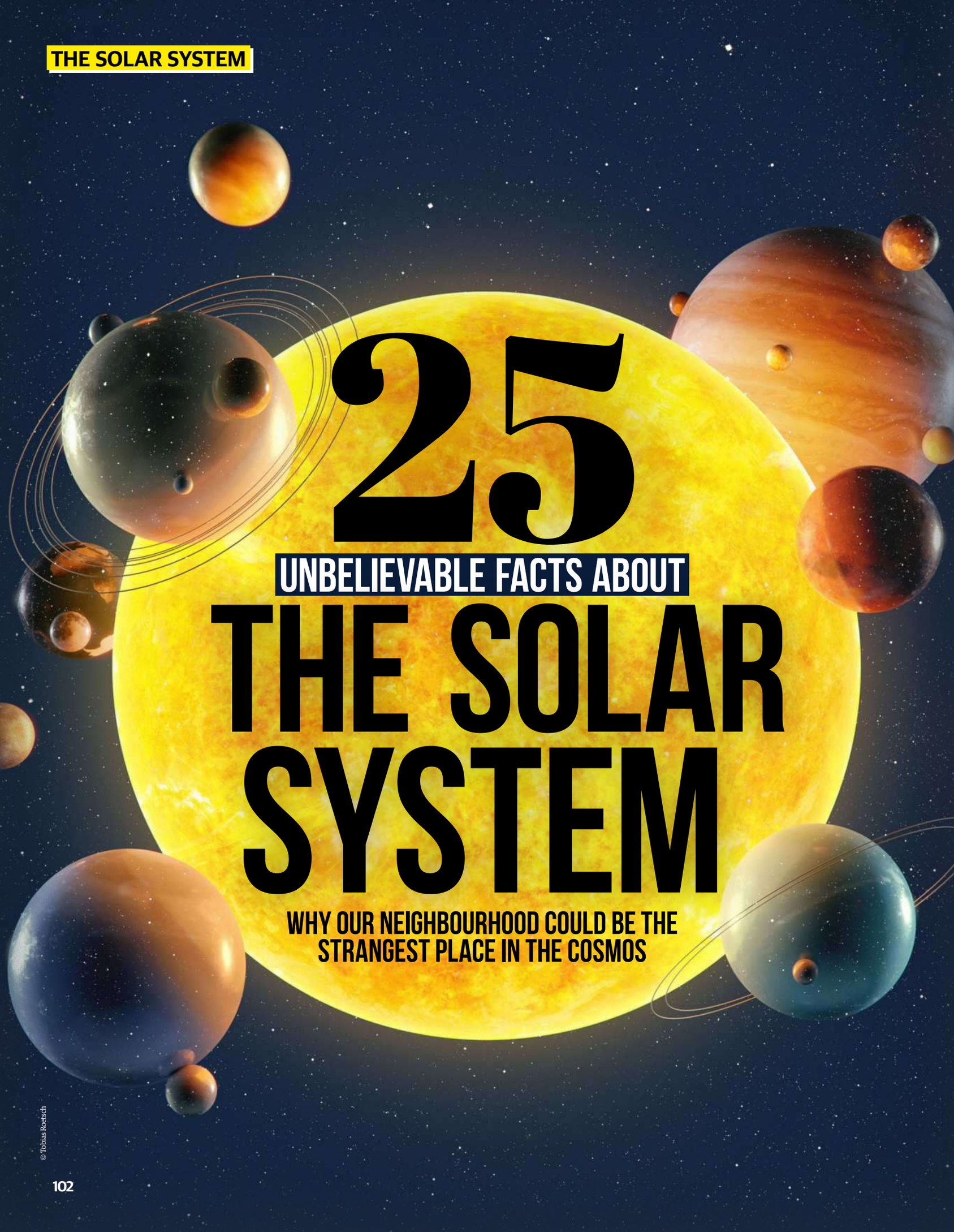


25 UNBELIEVABLE FACTS ABOUT THE SOLAR SYSTEM

WHY OUR NEIGHBOURHOOD COULD BE THE STRANGEST PLACE IN THE COSMOS

1 THE SOLAR SYSTEM IS REALLY BIG

NASA's Voyager 1 spacecraft was launched in 1977. More than three decades later, in 2012 it became the first human-made object to enter interstellar space by crossing the heliopause – the edge of the heliosphere. That's the boundary beyond which most of the Sun's ejected particles and magnetic fields dissipate. "If we define our Solar System as the Sun and everything that primarily orbits the Sun, Voyager 1 will remain within the confines of the Solar System until it emerges from the Oort Cloud in another 14,000 to 28,000 years," NASA says.

"THE MOON IS BOTH MIND-BOGGLINGLY DISTANT AND INCREDIBLY CLOSE DEPENDING ON HOW YOU THINK ABOUT IT"

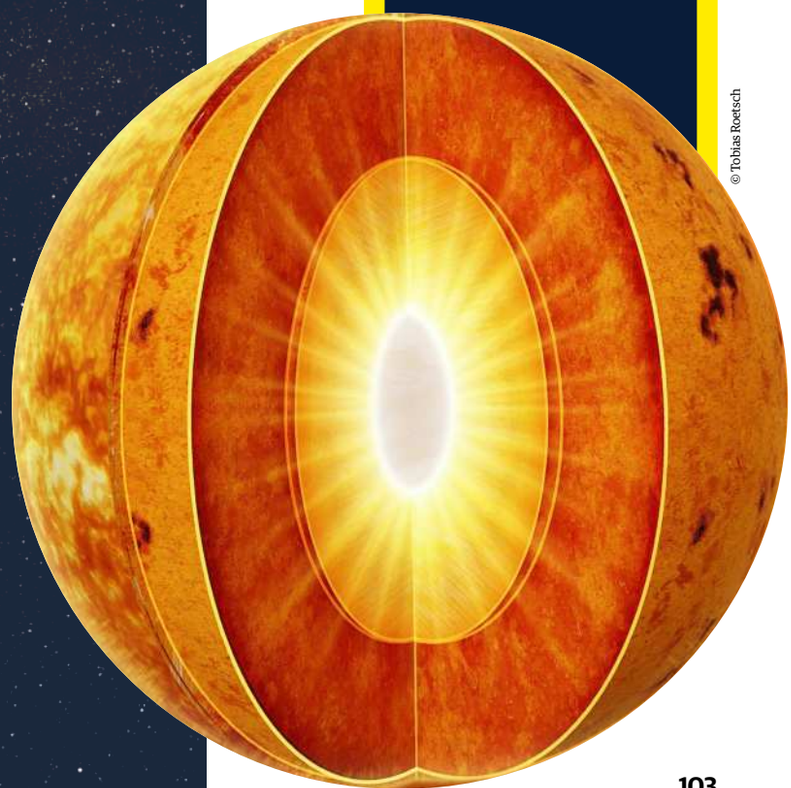
2 EVEN JUST OUR NEIGHBOURHOOD IS REALLY BIG

Depending on how carefully you do the calculations and how you arrange them, all of the planets in the Solar System could fit in between Earth and its Moon. The distance between Earth and the Moon varies as it orbits around us, as does the diameter of each of the planets – they're wider at their equators, so Saturn and Jupiter would have to be tilted sideways for this to work. But imagine lining them all up, pole to pole. They'd just barely squeeze in between us and our closest companion in space, blocking out the sky with their rings and gas giant bulk as they did so.

The Moon is the farthest from Earth we've ever sent humans, and it's both mind-bogglingly distant and incredibly close depending on how you think about it. Eight enormous planets could fit between here and there, and the distance from Earth to the Sun is more than 390 times the distance from Earth to the Moon. Scientists use an approximation of the Earth-Sun distance, also known as one astronomical unit, or AU, to compare distances within the Solar System. Jupiter is about 5.2 AU from the Sun, and Neptune is 30.07 AU from the Sun – around 30 times as far from the star as Earth.

3 THE SUN'S ATMOSPHERE IS HOTTER THAN ITS SURFACE

While the Sun's visible surface, the photosphere, is 5,500 degrees Celsius (10,000 degrees Fahrenheit), its upper atmosphere has temperatures in the millions of degrees. It's a large temperature differential with little explanation. NASA has several Sun-gazing spacecraft on the case, however, and they have some ideas for how the heat is generated. One is 'heat bombs', which happen when magnetic fields cross and realign in the corona. Another is when plasma waves move from the Sun's surface into the corona. With new data from the Parker Solar Probe – which recently became the first human-made object to 'touch' the Sun – coming in all the time, we're closer than ever to unlocking the mysteries at the heart of our Solar System.



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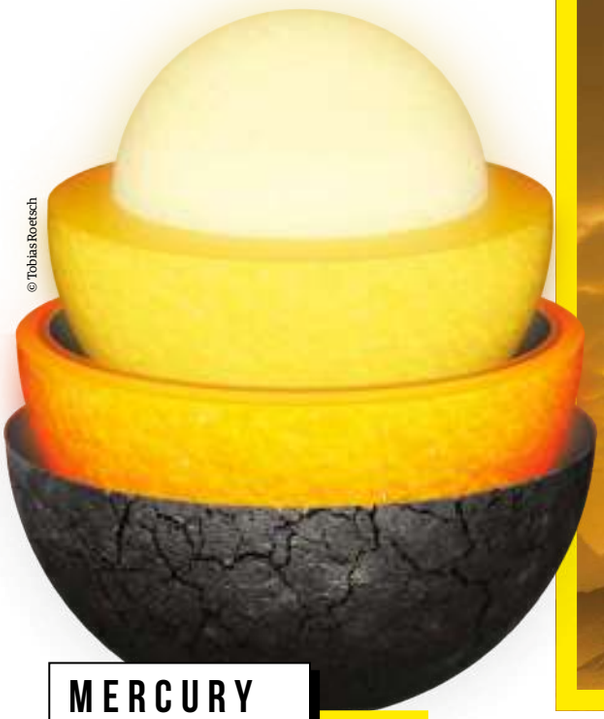

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4 MERCURY IS STILL SHRINKING

Mercury is already the smallest planet in the Solar System, and is the second-densest after Earth. And it's only getting smaller and denser. For many years, scientists believed that Earth was the only tectonically active planet in the Solar System. But that changed after the Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) spacecraft did the first orbital mission at Mercury, mapping the entire planet in high definition and getting a look at the features on its cratered surface.

In 2016, data from MESSENGER revealed cliff-like landforms known as fault scarps. Because the fault scarps are relatively small, scientists can be sure that they weren't created that long ago and that the small planet is still contracting 4.5 billion years after the Solar System was formed.

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5 VENUS IS SWEPT BY POWERFUL WINDS THAT COULD HARBOUR LIFE

Venus is a hellish planet with a high-temperature, high-pressure environment on its surface. Bone-dry and hot enough to melt lead, it's not exactly a welcoming environment, and has probably always been inhospitable to life. When the heavily shielded Venera spacecraft from the Soviet Union landed there in the 1970s, each lasted a few minutes, or at most a few hours, before melting or being crushed beyond their ability to function.

But even above its surface, the planet has a bizarre environment. Scientists have found that its upper winds flow 50 times faster than the planet's rotation. The European Venus Express spacecraft, which orbited the planet between 2006 and 2015, tracked the winds over long periods and detected periodic variations. It also found that the hurricane-force winds appeared to be getting stronger over time. A 2020 study that thrilled many astrobiologists detected phosphine, a possible sign of decaying biological matter, high in the Venusian clouds. Could they be a sign of life? Not without sufficient water, claim follow-up studies that firmly reject the possibility of life in Venus' dry and windy atmosphere.

6 EARTH'S VAN ALLEN BELTS ARE MORE BIZARRE THAN EXPECTED

There are several bands of magnetically trapped, highly energetic charged particles surrounding our planet, known as the Van Allen belts, named after the discoverer of the phenomenon. While we've known about the belts since the dawn of the Space Age, the Van Allen Probes, launched in 2012, have provided our best ever view of them. They've uncovered quite a few surprises along the way. We now know that the belts expand and contract according to solar activity. Sometimes the belts are very distinct from one another, and sometimes they swell into one massive unit. An extra radiation belt beyond the known two was spotted in 2013. Understanding these belts helps scientists make better predictions about space weather or solar storms.

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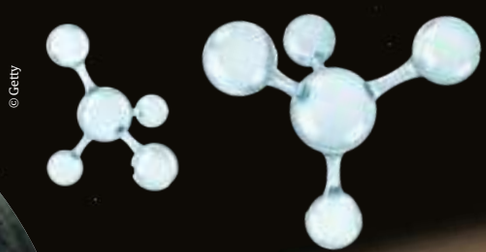
7 ORGANIC MOLECULES ARE EVERYWHERE

Organics are complex carbon-based molecules found in living things, but can be created by non-biological processes too. While organic molecules are common on Earth, they can be found in many other places in the Solar System too. Scientists have found organics on the surface of Comet 67P/Churyumov-Gerasimenko, for example. The discovery bolstered the case that organic molecules on Earth could have been brought to the surface from space. Organics have also been found on the surface of Mercury, on Saturn's moon Titan – giving Titan its orange colour – and on Mars.

"WHILE ORGANIC MOLECULES ARE COMMON ON EARTH, THEY CAN BE FOUND IN MANY OTHER PLACES TOO"



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8 A VALLEY ON MARS COULD SWALLOW THE GRAND CANYON

At 4,000 kilometres (2,500 miles), the immense system of Martian canyons known as Valles Marineris is more than ten times as long as the Grand Canyon on Earth. Valles Marineris escaped the notice of earlier Mars spacecraft flying over other parts of the planet and was finally spotted by the global mapping mission Mariner 9 in 1971. And what a sight it was to miss – Valles Marineris could stretch from New York to Seattle. The lack of active plate tectonics on Mars makes it tough to figure out how the canyon formed. Some scientists think that a chain of volcanoes on the other side of the planet, known as Tharsis Ridge, which includes Olympus Mons, somehow bent the crust from the opposite side of Mars. That cataclysmic force activated cracks in the crust, vast amounts of subsurface water that emerged to carve away rock and glaciers that crunched new pathways into the canyon system.

© NASA

9 MARS' BIGGEST VOLCANO IS BIGGER THAN HAWAII

While Mars seems quiet now, gigantic volcanoes once dominated the surface of the planet. This includes Olympus Mons, the biggest volcano ever discovered in the Solar System. At 602 kilometres (374 miles) across, the volcano is comparable to the size of Arizona. It's 25 kilometres (16 miles) high, or triple the height of Mount Everest, the tallest mountain on Earth. By volume, Olympus Mons is 100 times larger than Earth's largest volcano, Hawaii's Mauna Loa. Scientists speculate that volcanoes on Mars can grow to such immense sizes because gravity there is much weaker than it is on Earth. In addition, while Earth's crust constantly moves, the Martian crust likely doesn't, although the debate among researchers continues. The Hawaiian islands were formed as a hotspot in the mantle created a chain of volcanoes in the crust cruising by above it, so if the surface of Mars isn't moving, a volcano could build up for longer in one spot.

© Getty

10 THE GREAT RED SPOT IS SHRINKING

Along with being the Solar System's largest planet, Jupiter also hosts the Solar System's largest storm. Known as the Great Red Spot, it's been observed in telescopes since the 1600s and studied by modern instruments like those on NASA's Juno, which recently provided evidence that the storm is hundreds of miles tall and likely fed by winds from thousands of miles below. The storm has been a raging conundrum for centuries, but in recent decades another mystery emerged: the spot is getting smaller. In 2014 the storm was only 16,500 kilometres (10,250 miles) across, about half its historic size. The shrinkage is being monitored in professional telescopes, and also by amateurs. Amateurs are often able to make more consistent measurements of Jupiter because viewing time on larger, professional telescopes is limited and often split between different objects.

11 JUPITER'S MOON IO HAS HUGE VOLCANIC ERUPTIONS

Compared to Earth's peaceful Moon, Jupiter's moon Io may come as a surprise. The Jovian moon has hundreds of volcanoes and is considered the most active moon in the Solar System, sending plumes of sulphur up to 300 kilometres (190 miles) into its atmosphere. As such, Io's volcanoes emit around one tonne of gases and particles into space near Jupiter each second. Io's eruptive nature is caused by the immense forces the moon is exposed to nestled in Jupiter's gravitational well, as well as its magnetic field. The moon's insides tense up and relax as it orbits closer to and farther from the planet, generating enough energy for volcanic activity. Scientists are still trying to figure out how heat spreads through Io's interior, though, making it difficult to predict where the volcanoes exist using scientific models alone.

©NASA

"THE STORM HAS BEEN A RAGING CONUNDRUM FOR CENTURIES, BUT IN RECENT DECADES ANOTHER MYSTERY EMERGED: IT'S GETTING SMALLER"

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12 THERE IS WATER EVERYWHERE

Water was once considered rare in space. But water ice exists all over the Solar System. It's a common component of comets and asteroids. Water can be found as ice in permanently shadowed craters on Mercury and the Moon, though we don't know if there's enough to support prospective human colonies in those places. Mars also has ice at its poles, in frost and likely below the surface dust. Even smaller bodies in the Solar System have ice: Saturn's moon Enceladus and the dwarf planet Ceres, among others.

Scientists suspect Jupiter's moon Europa may be the most likely candidate for extraterrestrial life because against all expectations there's likely liquid water below its cracked and frozen surface. Europa, much smaller than Earth, may host a deep ocean that researchers suggest could contain twice as much water as all of Earth's oceans combined.

But we know that not all ice is the same. A close-up examination of Comet 67P by the European Space Agency's Rosetta spacecraft revealed a different kind of water ice than the kind found on Earth.

13 SATURN HAS A YIN-YANG MOON

Iapetus has a very dark hemisphere that always faces away from the planet and a very light hemisphere that always faces towards Saturn. Most asteroids, moons and planets are relatively uniform across their surfaces, but Iapetus sometimes shines brightly enough to be spotted by telescopes and then dims down by several magnitudes when oriented in the other direction. Research suggests that Iapetus is made mostly of water ice. As the moon's darker side faces the Sun, scientists hypothesise, water ice sublimates away from that area, leaving darker rock behind. That may have created a positive feedback loop, as dark material heats up more than bright, reflective ice – as the darker, warmer side of the moon loses its ice, it becomes easier to heat up each time it faces the Sun, hastening the loss of more ice.

14 TITAN HAS A LIQUID CYCLE

Another weird moon in Saturn's system is Titan, which hosts a liquid 'cycle' that moves material between the atmosphere and the surface. That sounds a lot like Earth's water cycle, but Titan's lakes are filled with liquid methane and ethane, possibly over a layer of water. Researchers hope to use data from Cassini-Huygens to tease out Titan's secrets before designing a submarine that will plumb the depths of the moon.

15 SATURN HAS A HEXAGONAL STORM

Saturn's northern hemisphere features a raging six-sided storm nicknamed 'the hexagon'. This towering, multilayered squall, has been present on the ringed planet for decades, if not hundreds of years. The storm was discovered in the 1980s, but was barely visible until the Cassini mission flew by between 2004 and 2017. Images and data from Cassini reveal the storm to be 300 kilometres (180 miles) tall, 32,000 kilometres (20,000 miles) wide and composed of air moving at about 320 kilometres (200 miles) per hour.

16 RINGS ARE MORE COMMON THAN WE THOUGHT

We've known about Saturn's rings since telescopes were invented in the 1600s, but it took spacecraft and more powerful telescopes built in the last 50 years to reveal more. We now know that every planet in the outer Solar System – Jupiter, Saturn, Uranus and Neptune – has a ring system. But the rings differ from planet to planet: Saturn's spectacular halo, made in part of sparkly, reflective water ice, is not repeated anywhere else. Instead the rings of the other giants are likely made of rocky particles and dust. Rings aren't limited to planets, either. In 2014 astronomers discovered rings around the asteroid 10199 Chariklo.

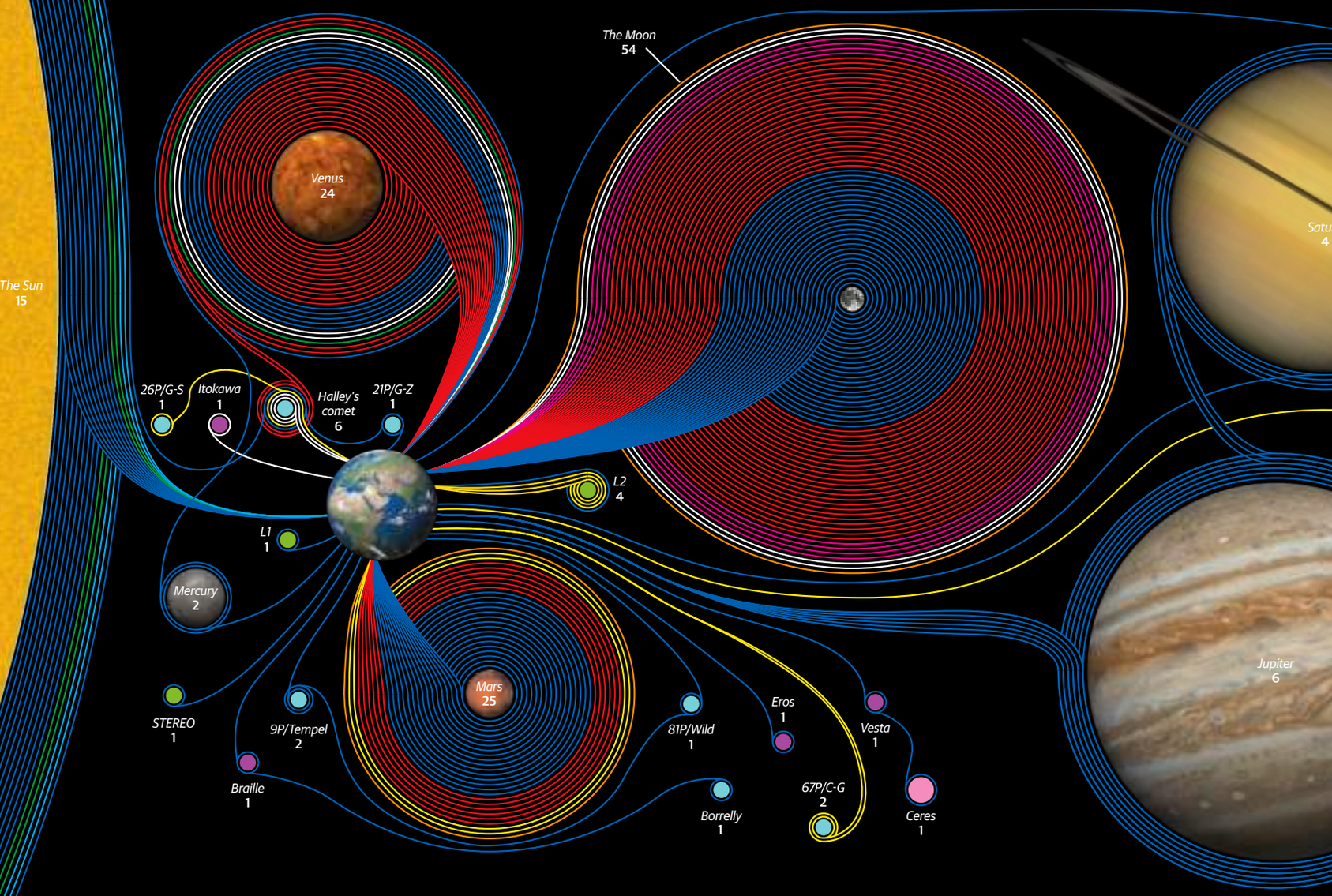
17 SPACECRAFT HAVE VISITED EVERY PLANET

We've been exploring space for more than 60 years, and have been lucky enough to get close-up pictures of dozens of celestial objects. Most notably, we've sent spacecraft to all of the planets in our Solar System – Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune – as well as two dwarf planets, Pluto and Ceres. The bulk of the flybys came from NASA's Voyager 1 and Voyager 2, which left Earth more than four decades ago and are still transmitting data from interstellar space. Between them the Voyagers clocked visits to Jupiter, Saturn, Uranus and Neptune thanks to an opportune alignment of the outer planets.

18 WORLDS COULD BE CONTAMINATED BY SPACECRAFT

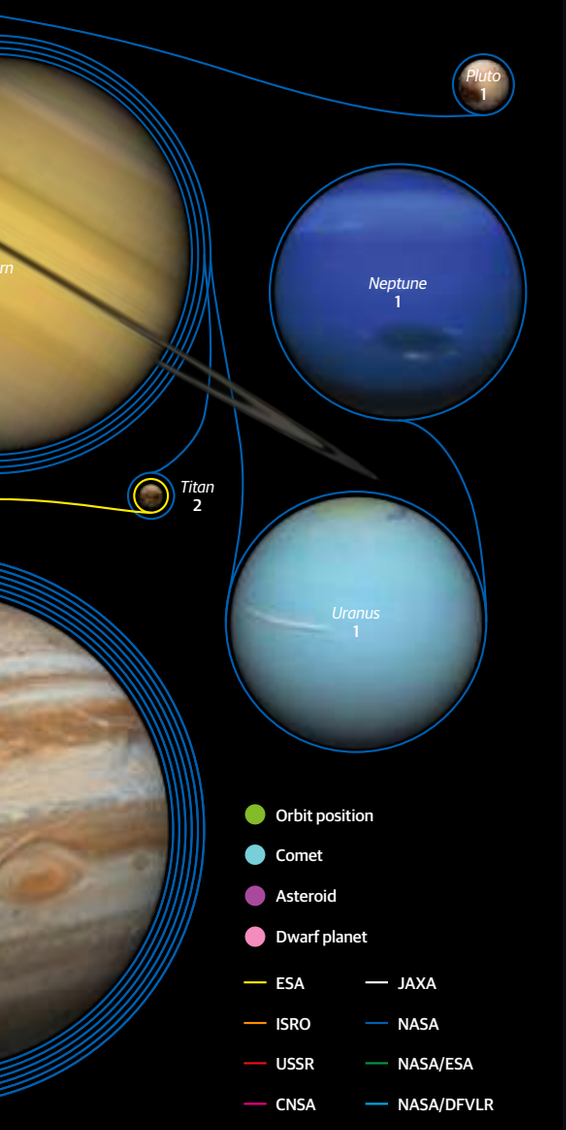
So far, scientists have found no evidence that life exists elsewhere in the Solar System. But as we learn more about how 'extreme' microbes live in underwater volcanic vents or frozen environments, more possibilities open up for where they could live on other planets.

Microbial life is now considered likely enough on Mars that scientists take special precautions to sterilise spacecraft headed to the planet. NASA chose to crash its Galileo spacecraft into Jupiter rather than risk it contaminating the potentially habitable oceans of Europa.

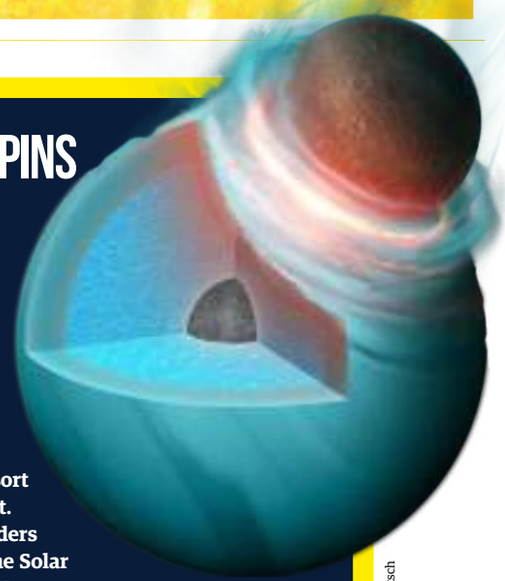


19 MOST COMETS ARE SPOTTED WITH A SUNGRAZING TELESCOPE

Comets used to be the province of amateur astronomers who spent night after night scouring the skies with telescopes. While some professional observatories also made discoveries while viewing comets, that began to change with the launch of the Solar and Heliospheric Observatory (SOHO) in 1995. Since then, the spacecraft has found more than 2,400 comets, which is a pretty productive side mission for a telescope meant to observe the Sun. These comets are nicknamed 'sungrazers'. Many amateurs still participate in the search for comets by picking them out from raw SOHO images. One of SOHO's most famous observations came when it watched the breakup of the bright Comet ISON in 2013.

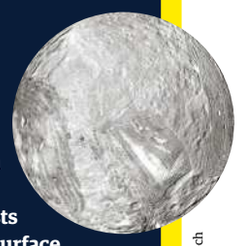


20 URANUS SPINS SIDEWAYS

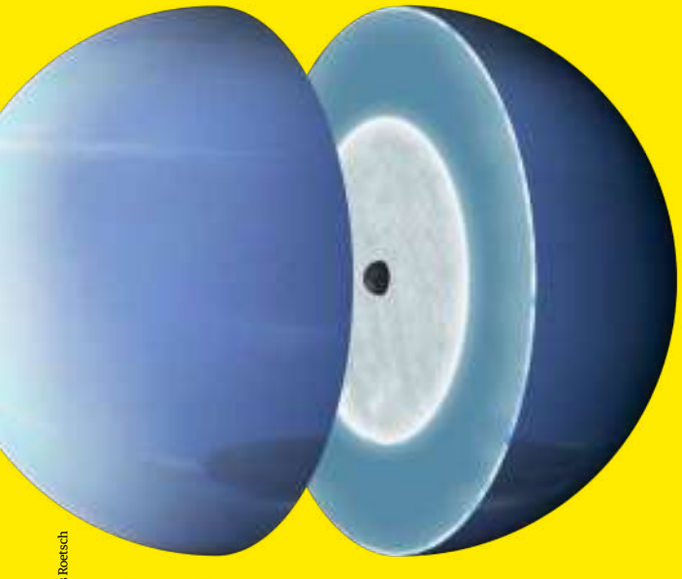


This gas giant of the outer Solar System is pretty weird on closer inspection. First, the planet rotates on its side, appearing to roll around the Sun like a ball. The most likely explanation for the planet's unusual orientation – about 90 degrees sideways compared to the other planets – is that it underwent some sort of titanic collision in the ancient past. Uranus' tilt causes what NASA considers to be the most extreme seasons in the Solar System. For about a quarter of each Uranus year – or 21 Earth years, as each Uranus year is 84 years long – the Sun shines directly over the north or south pole of the planet. That means for more than two decades on Earth, half of Uranus never sees the Sun at all.

21 WHAT HAPPENED TO MIRANDA?



One of the most bizarre moons in the outer Solar System is Miranda, a shadowy moon of Uranus observed only once when Voyager 2 got a glimpse in 1986. Miranda hosts sharp ridges, craters and other major disruptions on its surface that would usually be the result of volcanic action. Tectonic activity could cause that kind of surface, but Miranda is much too small to generate that kind of heat on its own. Researchers think that gravitational pull from Uranus could have generated the push-pull action needed to heat, churn and contort Miranda's surface. To know for sure, we'll need to send another spacecraft to check out the moon's unobserved northern hemisphere.



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22 NEPTUNE IS TOO HOT

Neptune is roughly 30 times as far from the Sun as Earth, and it gets correspondingly less heat and light. But it radiates far more heat than it's taking in and has far more activity in its atmosphere than planetary scientists would suspect, especially compared to nearby Uranus. Uranus is closer to the Sun and yet radiates about the same amount of heat as Neptune, and scientists aren't sure why. Winds on Neptune can blow up to 2,400 kilometres (1,500 miles) per hour. Is all that energy coming from the Sun, from the planet's core or from gravitational contraction? Researchers are working to find out.

23 THERE ARE MOUNTAINS ON PLUTO

A tiny world at the edge of the Solar System, scientists assumed the dwarf planet would have a fairly uniform, crater-pocked environment. That changed when New Horizons flew by in 2015, sending back pictures that altered our view of Pluto forever. Among the astounding discoveries were icy mountains that are 3,300 metres (11,000 feet) high, indicating that Pluto must have been geologically active as little as 100 million years ago. Geological activity requires energy, and the source of that energy inside Pluto is a mystery. The Sun is too far away from Pluto to generate enough heat for geological activity and there are no large planets nearby that could have caused such disruption with gravity.

24 PLUTO ALSO HAS A BIZARRE ATMOSPHERE

©NASA

Pluto's observed atmosphere broke all the predictions. As data from NASA's New Horizons flowed in, scientists analysed the haze and discovered some surprises. They found about 20 layers in Pluto's atmosphere that are both cooler and more compact than expected. This affects calculations for how quickly Pluto loses its nitrogen-rich atmosphere to space. The New Horizons team found that tonnes of nitrogen gas escapes the dwarf planet by the hour, but somehow Pluto can constantly resupply that lost nitrogen. The dwarf planet is likely creating more of it through geological activity.

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25 THERE MAY BE A HUGE PLANET AT THE SOLAR SYSTEM'S EDGE

In January 2015, California Institute of Technology astronomers Konstantin Batygin and Mike Brown announced – based on mathematical calculations and simulations – that there could be a giant planet lurking far beyond Neptune. Several teams are now on the search for the theoretical 'Planet Nine', and research suggests it could be located within the decade. This large object, if it exists, could help explain the movements of some objects in the Kuiper Belt, an icy collection of objects beyond Neptune's orbit. Brown has already discovered several large objects in that area that in some cases rivalled or exceeded the size of Pluto, but scientists are pursuing another theory, too – that Planet Nine could in fact be a grapefruit-sized black hole, warping space similarly to the way a gigantic planet would. Yet another team suggests that the weird movements of the far-flung Kuiper Belt occupants could be the collective influence of several small objects, not an undiscovered planet or black hole at all.

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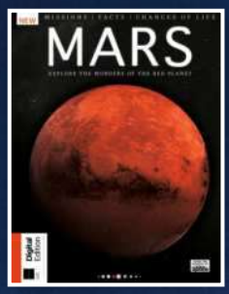

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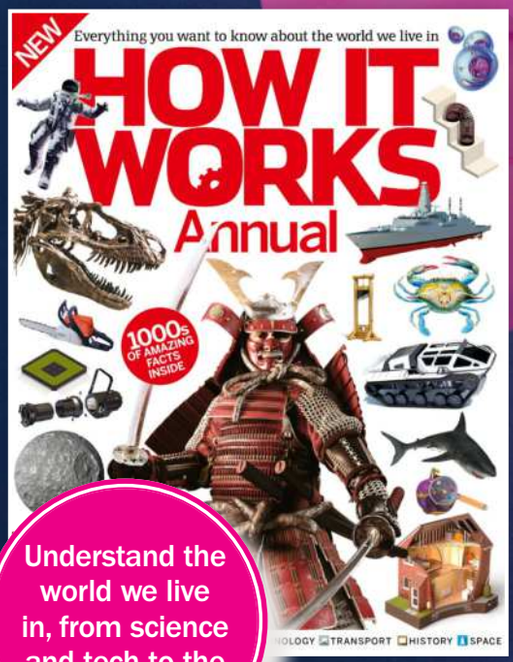

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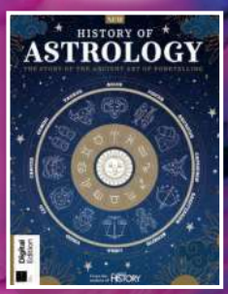

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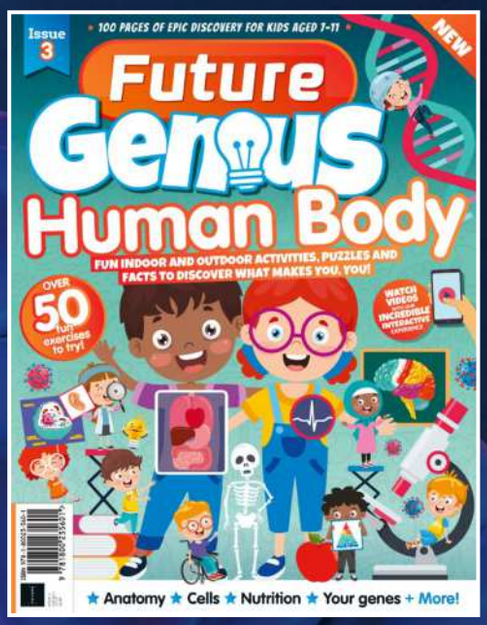

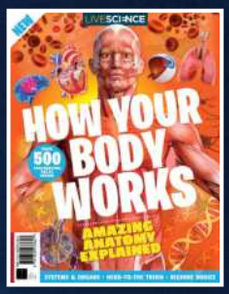

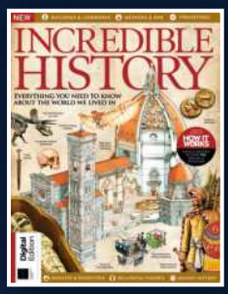

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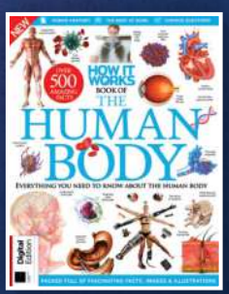

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